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FRACTIONAL EFFICIENCY OF A UTILITY BOILER BAGHOUSE. NUCLA GENERATING PLANT

Robert M. Bradway, et al

GCA Corporation

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16. ABSTRACT

The report gives results of an extensive testing program performed on a fabric filter baghouse operating on a small coal-fired utility boiler. Total mass loadings were obtained by sampling upstream and downstream using Method 5 techniques; particulate size distributions were obtained with instack impactors. A condensation nuclei counter/diffusion denuder system was also used for submicrometer sizing analysis, but the instrumentation was found to be difficult to work with and very sensitive to the static pressure of the sample stream. The results of 22 tests indicated a mean mass efficiency of 99.84 percent. Eleven tests were run at normal baghouse operating conditions and eleven were run at abnormal operating conditions. Statistical analyses show no significant influence of the abnormal operating conditions on particulate penetration.

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Dust Filters	Stationary Sources	13K
Utilities	Fabric Filters	
Boilers	Baghouses	13A
Coal	Particulates	21D
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FRACTIONAL EFFICIENCY OF A UTILITY BOILER BAGHOUSE

NUCLA GENERATING PLANT

by

Robert M. Bradway and Reed W. Cass

GCA Corporation
GCA/Technology Division
Bedford, Massachusetts 01730

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CONVERSION FACTORS FOR BRITISH AND METRIC UNITS

To convert from	To	Multiply by	To	Multiply by
^oF	^oC	$\frac{5}{9}$ (^{o}F-32)	—	—
ft.	meters	0.305	centimeters	30.5
ft.^{2}	meters^2	0.0929	centimeters^2	929.0
ft.^{3}	meters^3	0.0283	centimeters^3	28,300.0
ft./min. (fpm)	centimeters/sec.	0.508	meters/sec.	5.08×10^{-3}
ft.^{3}/min.	centimeters^3/sec.	471.9	meters^3/hr.	1.70
in.	centimeters	2.54	meters	2.54×10^{-2}
in.^{2}	centimeters^2	6.45	meters^2	6.45×10^{-4}
oz.	grams	28.34	grains	438.0
oz./yd.^{2}	grams/meter^2	33.89	grams/centimeter^2	3.39×10^{-3}
grains	grams	0.0647	—	—
grains/ft.^{2}	grams/meter^2	0.698	—	—
grains/ft.^{3}	grams/meter^3	2.288	—	—
lb. force	dynes	4.44×10^5	Newtons	0.44
lb. mass	kilograms	0.454	grams	454.0
lb./ft.^{2}	grams/centimeter^2	0.488	grams/meter^2	4880.0
in. H_2O/ft./min.	cm. H_2O/cm/sec.	5.00	Newtons/meter^2/cm/sec.	490.0
Btu	calories	252		

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SECTION I

CONCLUSIONS

The fabric filter baghouse tested during this program removed particulate emissions from a coal-fired boiler with a mean efficiency of 99.84 percent. Under the test conditions this resulted in a mean outlet loading of 0.0031 grains per dry standard cubic foot. At the time of testing frequent bag failures were being experienced because of poor flow distribution at the inlet to the bags. Even though the collection efficiencies determined in the present study were quite high, it is felt that significant improvement will be made when the bag wear problem is solved.

The median fractional efficiency for the baghouse over the range of 1 to 10 µm (99.4 to 99.8 percent) showed day-to-day variations but was generally highest for the larger particles. The collection efficiency for particles in the 2 to 6 µm range was nearly constant (~99.55 percent) but lower than for 8 to 10 µm particles (~99.7 to 99.8 percent) while collection of 1 µm particles (~99.4 percent) was generally lower than the 2 to 6 µm fraction.

Several deliberate changes were made in the baghouse cleaning cycle but none resulted in a statistically significant change in particulate penetration. Multiple regression analyses of several of the controllable and uncontrollable variables showed that penetration is most highly correlated with the ash content of the coal but that the correlation is negative. That is, the higher the ash content of the coal the lower the penetration. Assuming that higher ash content increases the inlet loading, this would seem to indicate that the baghouse smooths out input variations. That is, a relatively steady, low outlet concentration is achieved over a wide range of inlet loadings. Under these conditions the percent penetration would decrease as a result of the higher inlet concentration. Although our tests do not show a statistically significant relation between the inlet loading and ash content, we believe that some relationship between the inlet loading and the ash content, or other property that is related to ash content, must exist because the relationship between penetration and ash is, indeed, very strong.

The results of the multiple regression analysis also showed that, for the Nucla baghouse, the following changes in the cleaning cycle had no statistically significant effect on particulate penetration.

- Increase in repressure air duration from the normal 15 seconds to 60 seconds.
- Elimination of the repressure air.
- Elimination of the shake portion of the cleaning cycle, which was normally 10 seconds per compartment per cycle.
- Elimination during the sampling period of the cleaning cycle, which was nominally once every 2 hours, depending on the coal quality.
- Increase in the cleaning cycle to about once every half hour.

The multiple regression analysis showed that several variables had a significant effect on penetration. These included:

- Ash content of the coal.
- Time since last replacement of failed bags.
- Sulfur content of the coal.
- Steam load.
- Particulate loading entering the baghouse.
- Moisture content of the coal.

Several physical and chemical properties of the flue gas, coal and fly ash were also measured during the program. No attempt was made, however, to correlate these variables with particulate penetration.

SECTION II

RECOMMENDATIONS

It is recommended that more laboratory experimentation and actual field work be performed with the condensation nuclei counter system. One area which should be concentrated on is the preservation of the number and size distribution of submicron particles in the sample conditioning or dilution system. Also, a standardized method of counting submicron particles with an instrument other than the condensation nuclei counter needs to be developed to verify CNC measurements. Perhaps a technique of collection of the particles on a medium which is analyzed with an electron microscope could be utilized.

In the evaluation of high efficiency control devices for particle penetration as a function of particle size, there is a need for the development of high and low flow rate in-stack impactors. First, there is the problem of a high inlet loading necessitating a short sampling duration to prevent overloading of the stages of the Andersen in-stack impactor. The short sampling time is a source of possible error due to temporal variations in the inlet loading and to the inability to instantaneously adjust the flow rate through the impactor to precisely match the stack conditions at the time of sample extraction. An ideal impactor for the inlet would allow for an extended sampling duration equal to the sampling duration required by the outlet impactor. Second, there is the problem of the low outlet loading requiring an excessively long sampling period to obtain weighable samples on the stages of the Andersen in-stack impactor. An ideal outlet in-stack impactor would have a higher flow rate to reduce the sampling time to that required by the simultaneous Method 5 technique. In addition both inlet and outlet impactors should be designed to sample through a straight nozzle to reduce the particulate losses experienced with the nozzles utilized in the present study. The mean percentage of the mass caught in the inlet impactor probe was 20.9 percent with a standard deviation of 9.8 while the mean percentage of mass caught in the outlet impactor probe was 14.6 percent with a standard deviation of 8.6.

It has been learned from plant personnel that recent changes in the baghouse thimble plate have improved bag wear. One baghouse reportedly has seen 5 months of service without a bag failure and a short series of tests would be very useful in quantifying any significant improvement in baghouse performance. The tests should be performed only under normal operating conditions and should include size distribution measurements as well as Method 5 measurements.

SECTION III

INTRODUCTION

BACKGROUND

The work reported in this publication is one phase of a program whose purpose is to characterize the performance of several industrial size fabric filter systems. Of particular importance is the particulate removal efficiency of the baghouses as a function of particle size. The fractional particle size efficiency was determined by doing upstream and downstream sampling using inertial and diffusional sizing techniques and the total mass efficiency was determined utilizing simultaneous upstream and downstream Method 5 techniques.

Although fabric filtration technology has been successfully applied to a wide variety of industrial processes, there are several areas where baghouses have not been or are just beginning to be utilized. One of the recent applications is for the control of particulate emissions from coal-fired utility boilers. The potential use for baghouses on boiler flue gases is very large and yet the successful application in this area represents a significant advancement in the state of the art. Since the use of baghouses for this type of application is very limited, several different boiler and baghouse operating conditions were included in the characterization plan in an attempt to determine what parameters, if any, would effect a significant difference in fabric filter performance.

APPROACH

The fabric filter installation evaluated during this first phase of the program was on a small utility boiler in Colorado burning Western coal. The approach to the baghouse performance characterization was to perform a pretest survey to gain firsthand knowledge of the facility and determine what operational parameters could be varied. This information was then used as the basis for a test plan which was designed to include enough normal base line operation to statistically define performance boundaries. Abnormal operating conditions were intermittently spaced throughout the test plan and the sampling results compared with those of normal operation to see if baghouse performance had been significantly altered. The baghouse parameters that were changed during this study included repressure air duration (0, 15, 60 seconds), number of shakes per cleaning cycle (0, 10) and the number of cleaning cycles per test (0 to 14).

Although the operation of the baghouse was the only parameter to be deliberately changed, several uncontrollable variables were present. These uncontrolled variables were closely watched to detect their effect on the test results. The instruments in a van operated by Control Systems Laboratory personnel monitored the flue gas for sulfur dioxide, nitric oxide, carbon monoxide and oxygen during several of the tests. In addition, coal samples were taken routinely to provide information on the coal's ash and sulfur content. Also, copies of plant operating logs were obtained so that steam rate, coal consumption, and baghouse pressure drop variations could be identified.

SECTION IV

NUCLA, COLORADO GENERATING STATION

The Nucla Station of the Colorado Ute Electric Association is located in Nucla, a small town in southwestern Colorado. The plant, pictured in Figure 1, is comprised of three 13 megawatt generators each with its own Springfield boiler having a capacity of about 120,000 pounds of steam per hour. The boilers are the stoker-fired traveling grate type with fly ash reinjection and are fed at approximately 15,500 pounds of coal per hour. The coal is mined locally and trucked to the power plant.

The flue gas leaving the boiler economizer passes a baffle designed to remove the very large particles and then flows to the baghouse through a horizontal duct. Six sampling ports on the inlet duct afford access for sampling the dust laden gas entering the baghouse. The flue gas is pulled through the baghouse by an induced draft fan and the filtered gas stream is exhausted to a 100 foot stack. Sampling ports are located on the 5.5 foot diameter stack 46 feet above the outlet of the induced draft fan. The general arrangement of the system is presented in Figure 2.

Each boiler is served by a Wheelabrator-Frye size 814, Model 264, Series 8, Six Module Dustube Dust Collector. The six baghouse compartments contain 112 graphite silicon coated fiberglass bags per compartment. Each bag measures 8 inches in diameter by 264 inches in length for a total cloth area of 30,964 square feet per baghouse. At the designed flow rate of 86,240 acfm this would result in an air to cloth ratio of 2.79 to 1.

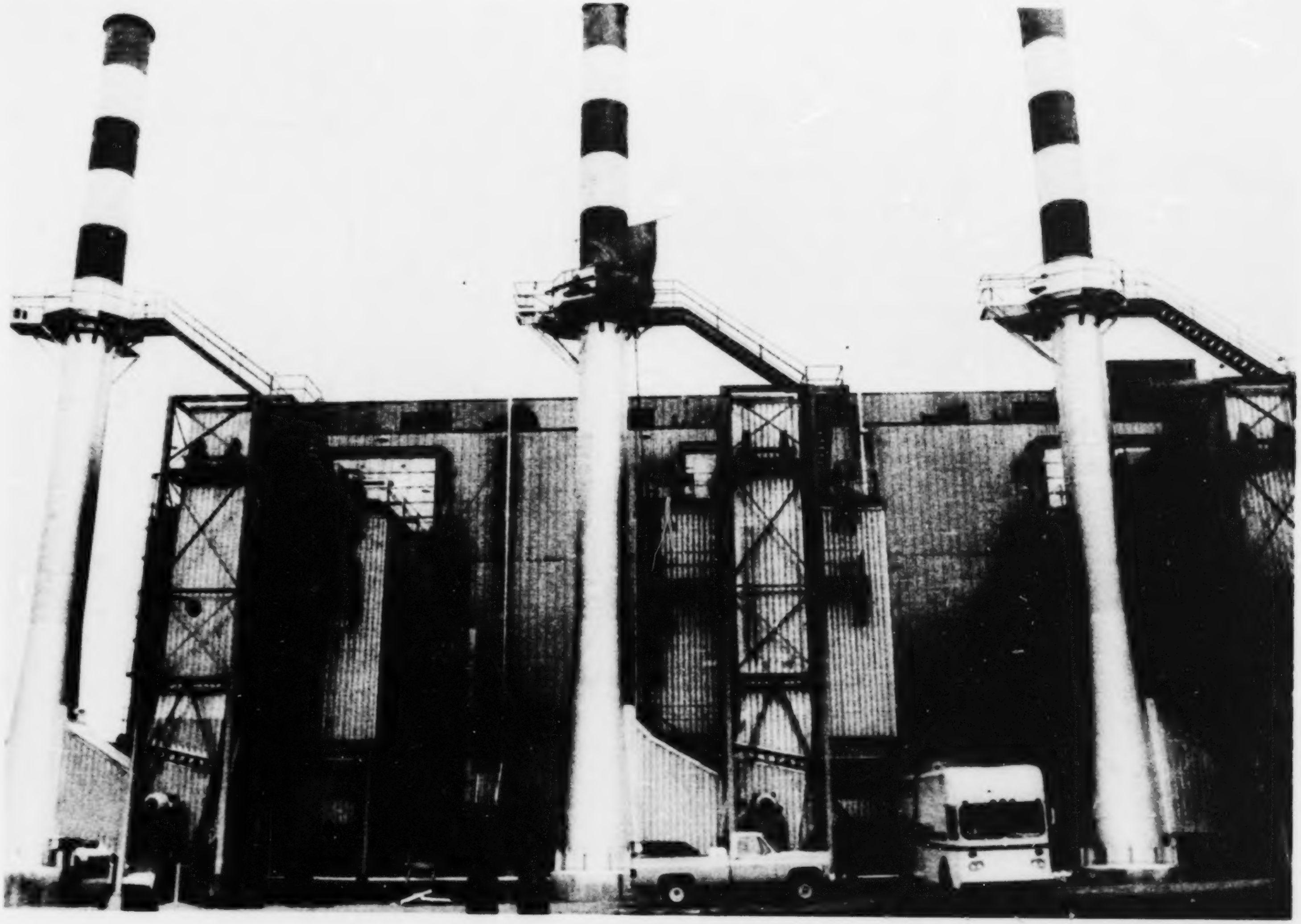


Figure 1. Nucla generating station

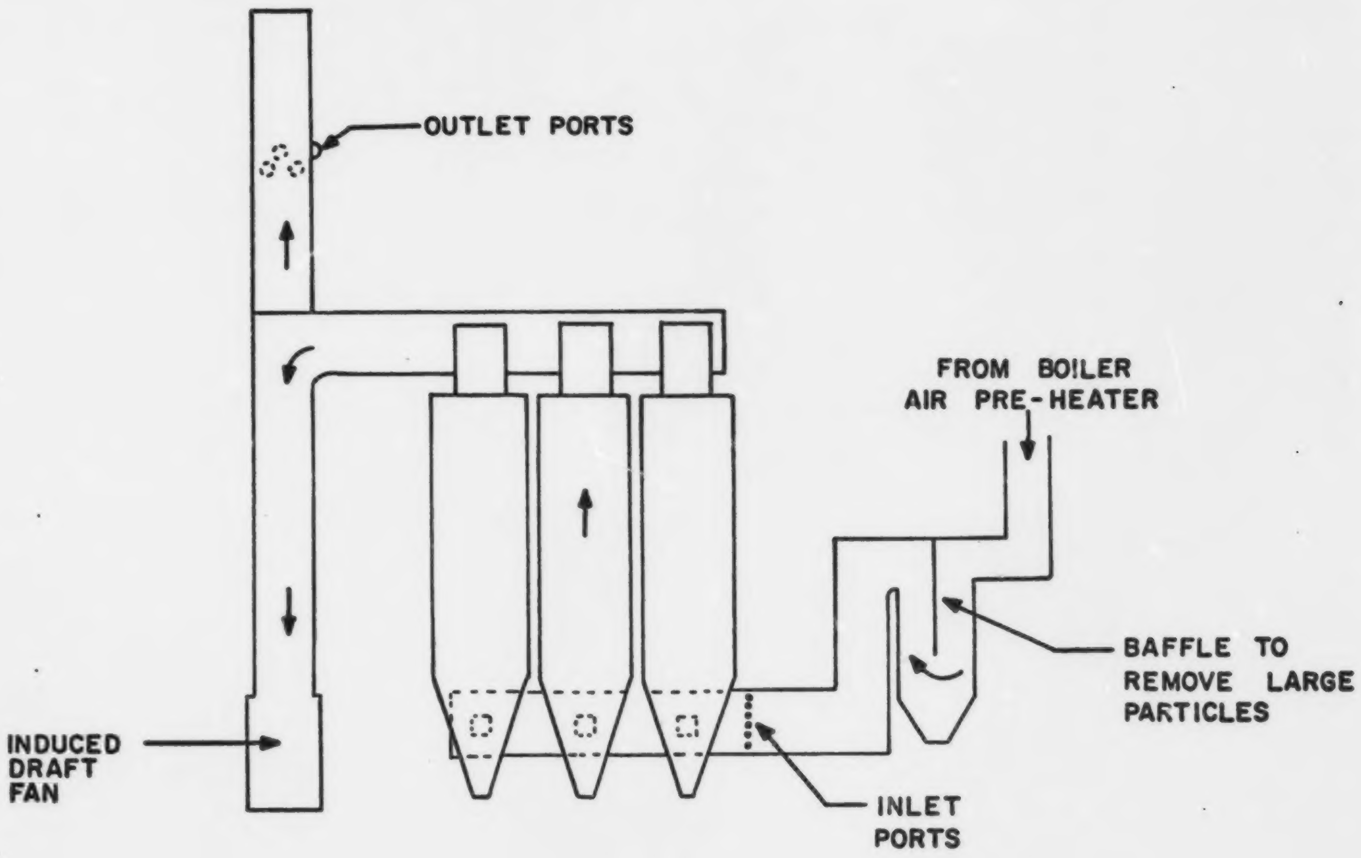

OUTLET PORTS
FROM BOILER AIR PRE-HEATER
BAFFLE TO REMOVE LARGE PARTICLES
INDUCED DRAFT FAN
INLET PORTS

Figure 2. Flue gas cleaning system

The bags used at Nucla have the following specifications according to the manufacturer, W. W. Criswell Company. The fabric material has a weight of 10.5 oz/yd^2 with a 66 x 30 thread count and the weave is a 3 x 1 twill. The warp yarn is a filament and the fill is a bulked yarn. Actual physical characterization tests on a new and a used bag from Nucla are presented in Table 1. Although it is impossible to determine how much service the used bag had seen, it is estimated that the maximum exposure that any bag could have seen is the 6 months since the baghouse was put on line in March 1974.

A combination of shaking and reverse air flow is used to clean the bags. The normal cleaning cycle, shown in Table 2, is actuated by a pressure transducer near the inlet to the induced draft fan. The pressure switch is normally set to initiate cleaning when the pressure drop across the bags exceeds about four inches of water. Once started, the cleaning cycle proceeds through all six compartments with a 17 second interval between compartments. A typical pressure drop trace is shown in Figure 3. The cleaning cycles are clearly evident and the sequence of switching to each compartment can be seen. The pressure drop across the baghouse is about 1.2 inches of water column lower after cleaning.

The repressure air (also reverse air or collapse air) is supplied by a separate blower that constantly circulates 5,600 cfm of flue gas from the outlet side of the baghouse. When no compartment is undergoing repressure, the gas is exhausted back into the duct leading to the induced draft fan. When repressuring is initiated, the main damper is already closed and the repressure damper opens allowing the filtered flue gas to flow through the dirty bags in the opposite direction of normal filtration at a velocity of 1.09 fpm. This gas then exits the compartment and joins the dirty flue gas entering the remaining five compartments.

Table 1. RESULTS OF PHYSICAL CHARACTERIZATION TESTS ON FABRIC FILTER BAGS

	New bag	Used bag, middle	Used bag, bottom
ASTM D1910, Sample weight, oz./sq. yd.			
range	7.4 - 7.5	7.7 - 7.8	11.3 - 11.7
average	7.4	7.8	11.4
ASTM D1777, Sample thickness, inches			
range	0.0135 - 0.0156	0.0139 - 0.0158	0.0149 - 0.0169
average	0.0147	0.0147	0.0156
ASTM D737, Air permeability, cfm/sq.ft.			
range	83.5 - 91.8	30.8 - 48.2	30.8 - 48.2
average	86.5	38.6	38.6
ASTM D1682, Breaking strength and elongation			
Breaking strength, lbs			
Warp: range	168.6 - 210.0	117.0 - 225.0	102.0 - 135.0
average	186	166	116
Fill: range	82.2 - 116.0	35.1 - 100.5	54.6 - 96.1
average	104	66.5	73.1
Elongation to break, percent			
Warp: range	8.9 - 11.7	6.2 - 8.1	6.0 - 8.1
average	10.7	7.6	6.9
Fill: range	4.6 - 5.2	2.4 - 4.0	2.0 - 3.7
average	4.8	3.1	2.9
Flexural rigidity, lbs $(in.)^2$/in. width			
average	6.26×10^{-4}	1.99×10^{-3}	2.04×10^{-3}

Table 2. NORMAL CLEANING SEQUENCE FOR EACH COMPARTMENT

Event	Duration, seconds	Damper positions
Settle	54	Main damper closed, repressure damper closed
Repressure	15	Main damper closed, repressure damper open
Settle	56	Main damper closed, repressure damper closed
Shake	10	Main damper closed, repressure damper closed
Settle	56	Main damper closed, repressure damper closed
Repressure	15	Main damper closed, repressure damper open
Settle	34	Main damper closed, repressure damper closed
		Main damper open, repressure damper closed
Interval	17	
		Initiate next compartment cleaning

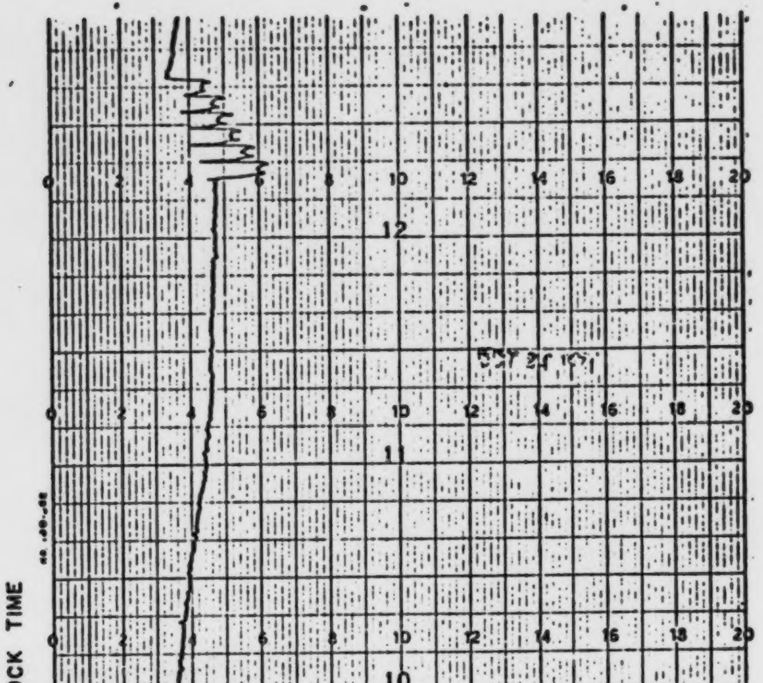


Figure 3. Typical pressure drop trace

Following the first reverse air flow and after about 1 minute of settle time the bags are shaken. The amplitude is not known, and will not be divulged by the manufacturer, but the frequency was measured at 4 cycles per second. The shaking action appeared quite gently and is most likely utilized to insure loosening of the cake from the bag.

The estimated capital cost for the baghouse installation is presented in Table 3. It should be pointed out that the cost data in Table 3 is for the three baghouses and includes some items not normally included in capital cost comparisons. For example if only the cost of the baghouse collectors is used, one would calculate about $2.50/acfm while the inclusion of all items in Table 3 would result in over $10/acfm initial capital cost.

Table 3. ESTIMATED CAPITAL COST FOR THE NUCLA BAGHOUSE INSTALLATION AS OF OCTOBER, 1974

Item	Costs	Percent
Baghouse collectors	$ 631,168	24.23
Ash system	86,332	3.31
Miscellaneous equipment and materials	219,083	8.41
Painting	61,000	2.34
General construction	1,193,080	45.80
Engineering (consultant)	294,383	11.30
C-U project manager cost	120,000	4.61
Total	$2,605,046	100.00

The three baghouses at Nucla are identical but it was prudent to restrict testing to only one. Plant personnel suggested number 2 boiler baghouse as being the most convenient so all tests were performed on that unit. Number 2 boiler baghouse was also selected because it has four ports installed in the stack allowing the Andersen Impactors to be run for the entire test period without being disturbed.

SECTION V

EQUIPMENT AND METHODS

Several types of sampling techniques were employed during the test program. Some methods were straightforward and do not require extensive descriptions while other techniques were novel and will be described in some detail. In addition, the large difference in particulate concentration between the inlet and outlet necessitated different sampling strategies at each location. Whenever possible, however, the inlet and outlet samples were collected over the same time period so that the effect of temporal variations on plant operations would be minimized.

METHOD 5 MEASUREMENTS

The particulate mass concentration at the inlet was determined using a RAC sampling train based on the design criteria as described in the Federal Register, Vol. 36, No. 247, Part II, December 23, 1971. The sampling location is nonideal in terms of upstream and downstream distances from disturbances but is the only access between the knockout baffle and the baghouse. The location of the inlet sampling ports is shown schematically in Figure 4 and pictorially in Figure 5. As one would suspect from the configuration, and as confirmed by the tests, the flue gas velocity is higher on the bottom half of the duct. A typical vertical flow profile is shown in Figure 4. The horizontal flow profile is only slightly skewed, with a somewhat higher flow near the back of the duct.

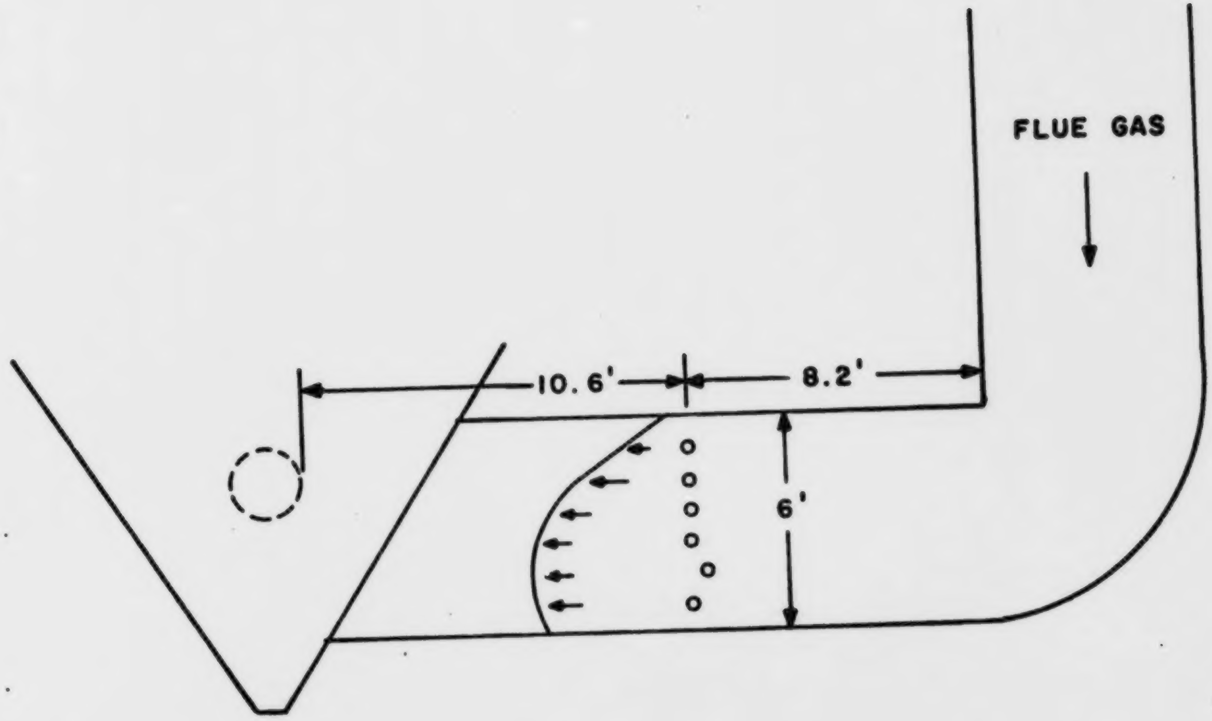

FLUE GAS
8.2'
10.6'
6'

Figure 4. Schematic of baghouse inlet duct showing sampling port locations

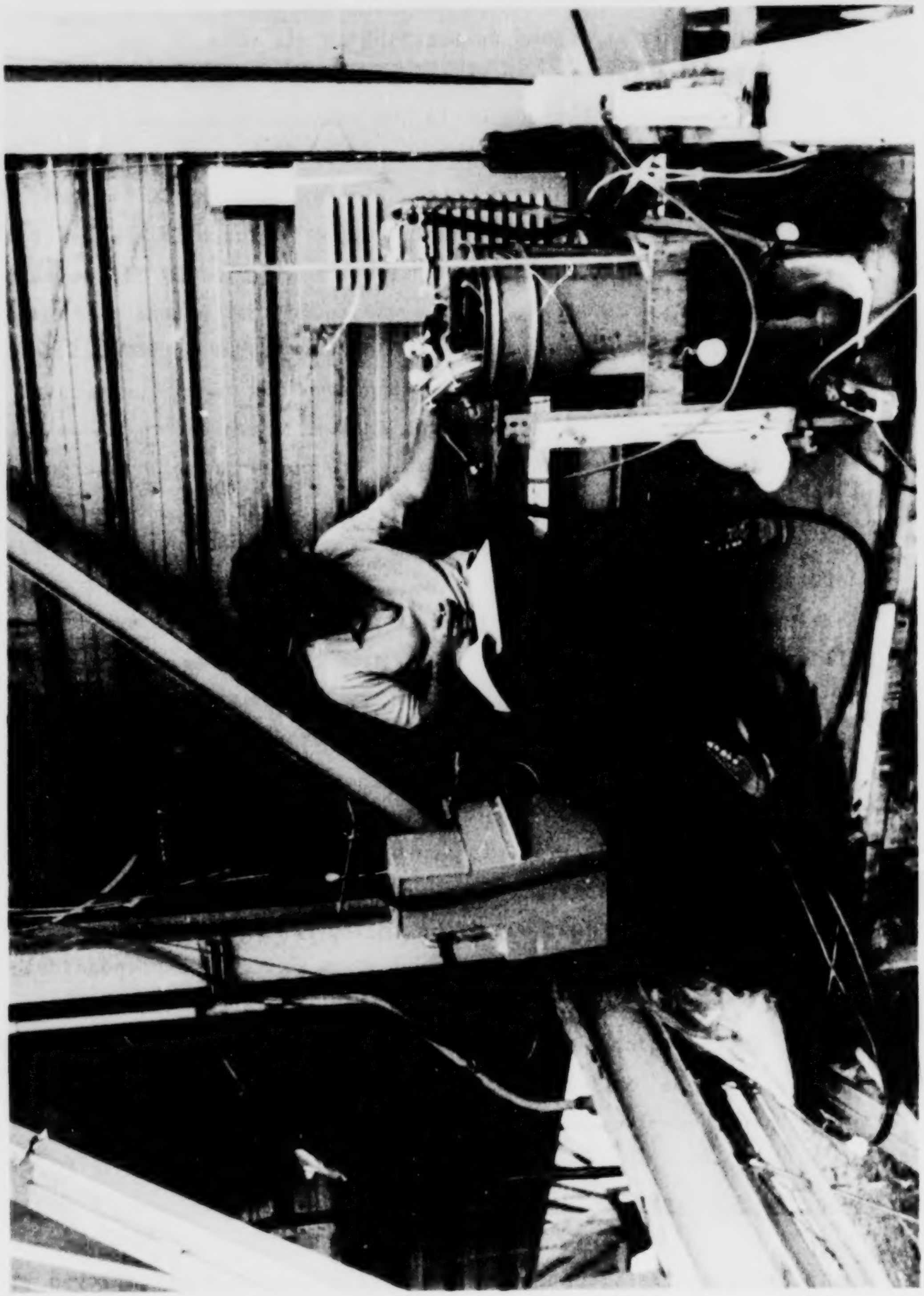


Figure 5. Baghouse inlet sampling location

Traversing was accomplished by sampling at six equally spaced points in the duct for each of the six ports as shown in Figure 7. Since the ports were not perfectly spaced in the vertical direction, it was impossible to traverse a duct with equal areas. The sampling array consisted of 36 points with each point being sampled for 10 minutes. This resulted in 6 hours of actual sampling time for each inlet mass loading test. The extended inlet sampling time was dictated by the results of the pretest survey, during which it was found that 6 hour tests were necessary to obtain weighable samples on the stages of the outlet Andersen impactor. The extraordinarily long sampling time necessitated two to three changes of the RAC cyclone and filter during each run but the strategy was to match as nearly as possible the outlet sampling period.

The particulate mass concentration of the outlet was determined using an Aerotherm high flow rate version of the standard EPA Method 5 train. This unit was utilized because it allowed collection of more mass on the filter per unit time at the very low mass loading downstream of the baghouse. The high volume train was operated without the cyclone precollector to avoid the unnecessary weighing errors introduced by its use at such low concentrations.

The outlet sampling location is shown pictorically in Figure 6 and the cross section schematically in Figure 8. This was an ideal sampling site with over eight duct diameters to the nearest downstream disturbance and an equal distance upstream to the stack exit. Two perpendicular diameters were traversed with six points per traverse. Each point was sampled for 30 minutes which resulted in a total sample time of 6 hours. Although a shorter sample time could have been utilized with the high volume train, simultaneous sampling with the impactors was again the objective.

Impactor Measurements

Particle size classification by inertial separation was employed to determine the size distributions of the particulates entering and leaving

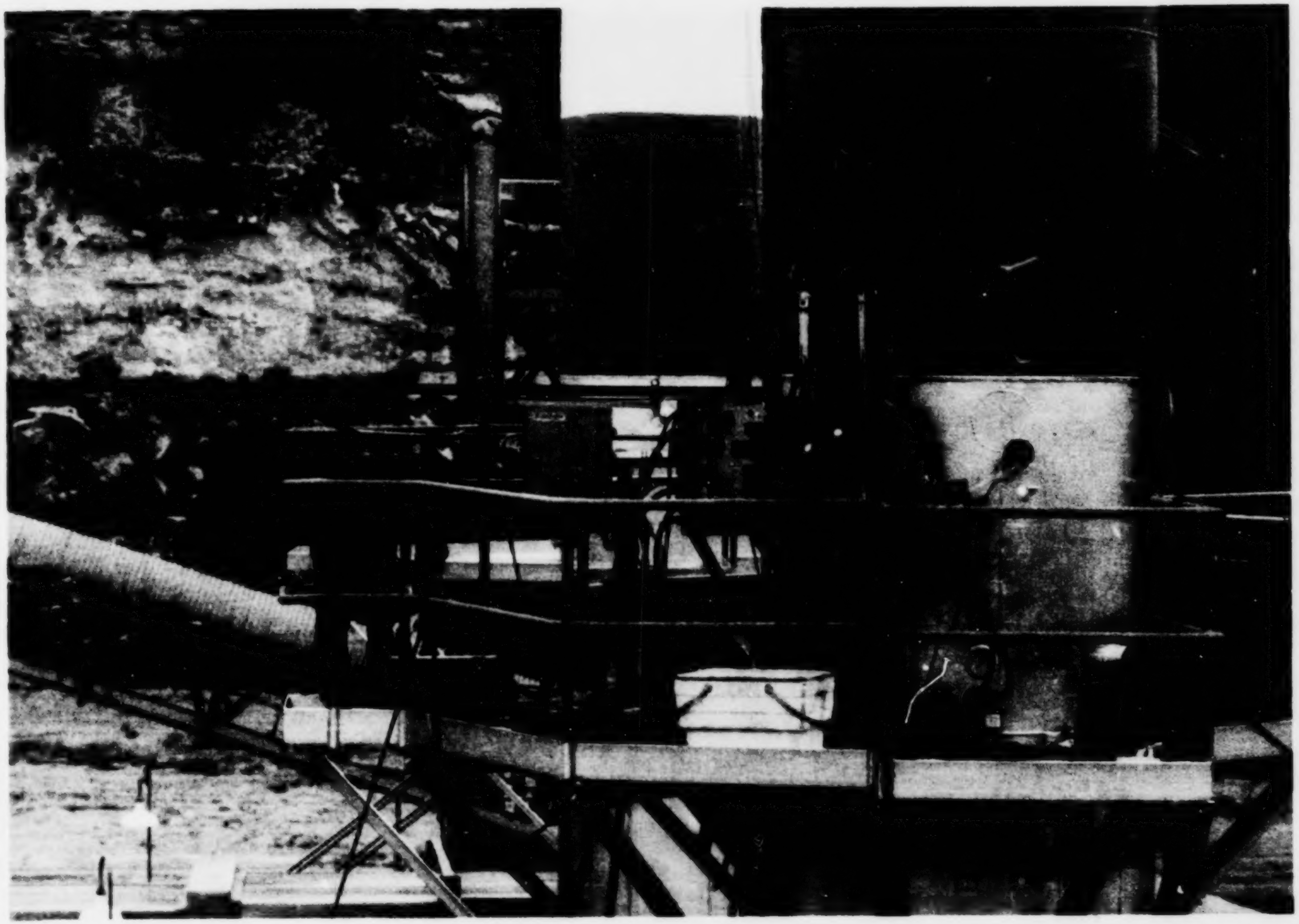


Figure 6. Baghouse outlet sampling location

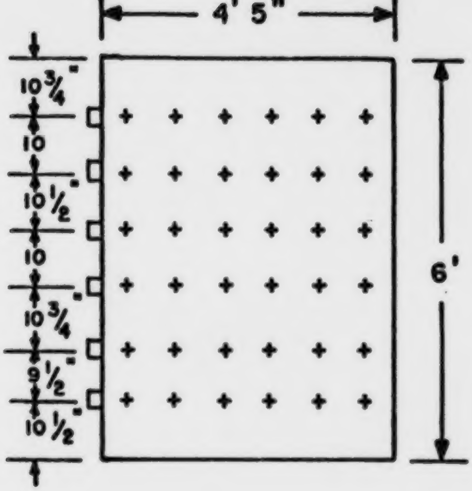

4' 5"
6'
10¾"
10
10½"
10
10¾"
9½"
10½"

Figure 7. Cross section of the baghouse inlet duct showing sampling points

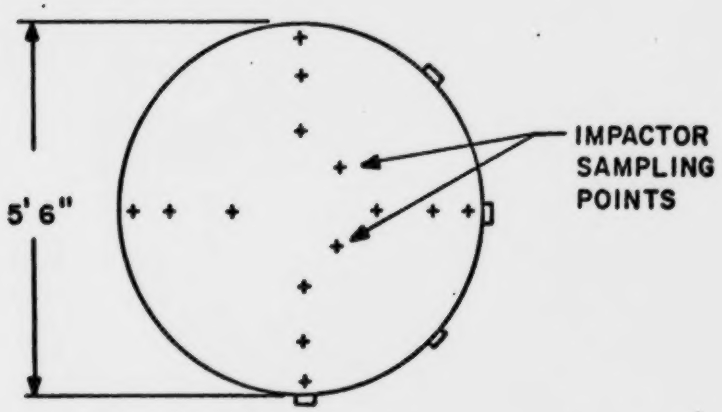

5' 6"
IMPACTOR SAMPLING POINTS

Figure 8. Cross section of baghouse outlet sampling location showing sampling points

the baghouse. Andersen Mark III in-stack impactors were used for particles over the size range of 0.5 μm to about 20 μm during the test program. These eight stage cascade impactors utilize glass fiber substrates as the collection media in order to minimize the tare weights. These impactors require a great deal of time and care for assembly and disassembly but no serious problems were encountered.

One disadvantage of all impactors is their inability to sample isokinetically while traversing a stack or duct. As the velocity changes going from one sampling point to the next the sampling rate of an impactor cannot be changed to match isokinetic conditions because the size cutoff for each stage would be changed and the results would be meaningless. One can, of course, traverse the gas stream using only one flow rate and, while the size cutoffs for each impactor stage are held constant, any spatial variations in stack gas velocity will result in anisokinetic sampling conditions. Alternatively one can forego traversing and sample at a single point in the stack at one flow rate that matches the gas velocity. In this case one cannot adjust for any temporal change in velocity at the sampling point and, of course, the spatial distribution of particulates is assumed to be uniform. This type of sampling is well suited for steady state operations with sampling ports located where the gas stream is well mixed even though the velocity profile is not flat. Preliminary measurements during the pretest survey indicated that such was the case at the baghouse outlet sampling location so traversing was not utilized.

Two impactors were run during each test at the outlet and their sampling locations in the stack are shown in Figure 8. Access to those points was afforded by two perpendicular ports that were below and 45 degrees offset from the ports used for total mass measurements. The impactors were put in the stack with the nozzles pointing with the flow of the gas stream 1/2 hour before sampling was begun. This was done to heat the impactors to the temperature of the flue gas so that condensation would not occur when sampling was initiated. Sampling was begun by turning the impactor nozzle into the gas stream and adjusting the flow so that the nozzle velocity matched the duct velocity which had been measured with a pitot static tube at each sampling point. The sample flow rates were not changed for the duration of the run and were maintained by keeping constant pressure drops across calibrated orifices.

The high particulate loading at the inlet dictated very short sampling times. Although it would have been preferred to match the inlet and outlet impactor runs, no more than five minutes sampling at the inlet could be tolerated without overloading the top stages. Consequently an impactor run was made each morning by first heating the impactor in the duct for half an hour and then sampling isokinetically for five minutes. The impactor was allowed to cool, disassembled and then reloaded so that a second run could be made in the afternoon.

In all impactor runs the nozzle size was selected such that actual flow rates through the impactors would be at, or near, 0.5 cfm while matching isokinetic conditions. Although the impactors were originally designed for flowrates up to 1.0 cfm, considerable particle bounce sometimes occurs at the higher flowrates.

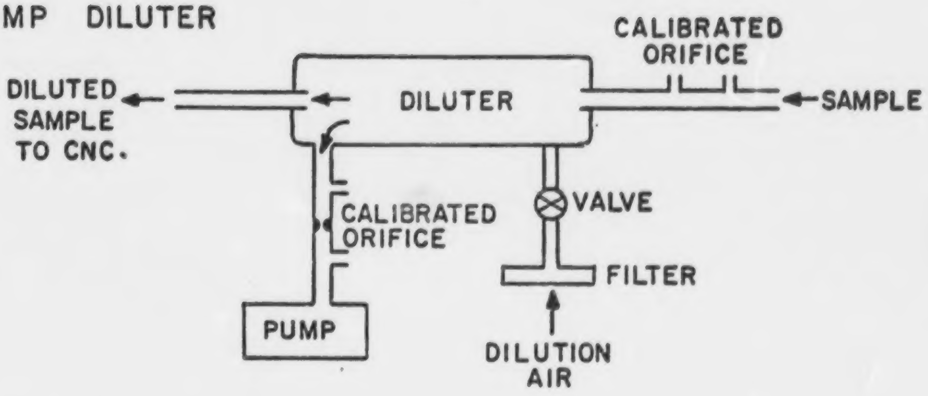
Condensation Nuclei Counter Measurements

The penetration of submicron particles through the baghouse was determined by sampling the effluent stream before and after the baghouse with a Condensation Nuclei Counter (CNC) and a Diffusion Denuder (DD). The particle concentration was measured by a Rich Model 100 CNC and the particle sizing was determined using a DD with the CNC.

The CNC is designed to measure particles between 0.0025 μm and 0.5 μm in the concentration range of 1000 to 300,000 particles/cc. When working with an aerosol that has a very large number of submicron particles, it was therefore necessary to dilute the sample stream so the concentration is within the CNC's measurement range. In addition, when sampling a hot, corrosive flue gas, substantial cooling of the sample stream must be accomplished to protect the CNC. Diluters provided the necessary cooling without subsequent condensation which results in the removal of submicron particles. Three diluters were fabricated. In a diluter, the sample stream is mixed with filtered air and the flow rates of the sample and diluted streams are measured with calibrated orifices. The flow rates are used to calculate the amount which the sample stream is diluted. The pump diluter shown in Figure 9a draws a sample through an orifice, then the sample flow mixes with a regulated flow of filtered air in the diluter body. The major portion of the diluted sample is drawn through an orifice by a pump and exhausted, while the remaining flow is drawn either directly to the CNC which measures the sample flowrate or through more diluters. This diluter is capable of providing a maximum dilution of approximately 375 to 1.

The air ejector diluter shown in Figure 9b is limited to a maximum dilution of approximately 10 to 1. It is most valuable because of its ability to draw a sample from a location where the pressure is below atmosphere and to discharge the diluted sample at a pressure above atmospheric. It was found during the tests that the CNC would not operate properly when the pressure of the sample entering the CNC was too far below atmospheric. In the air ejector diluter, the sample is drawn through an orifice by an air ejector in which the sample stream and a filtered compressed air stream are mixed before being discharged through an orifice which meters the combined flow.

Figure 9c shows a diluter capable of providing a 12 to 1 dilution. A capillary tube meters the sample flow which is combined with regulated filtered dilution air in a tee. The combined sample and dilution flow is measured by the CNC rotameter, which is used to monitor the flow rate to the CNC. The capillary tube diluter was used primarily to vary the sample flow rates through the DD to provide sizing data.


(a) PUMP DILUTER
CALIBRATED ORIFICE
DILUTED SAMPLE TO CNC.
DILUTER
SAMPLE
CALIBRATED ORIFICE
VALVE
FILTER
PUMP
DILUTION AIR

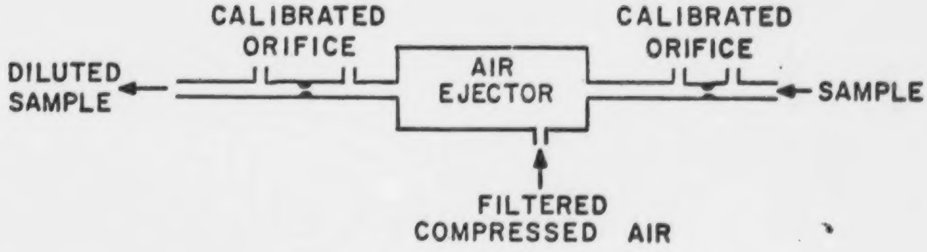
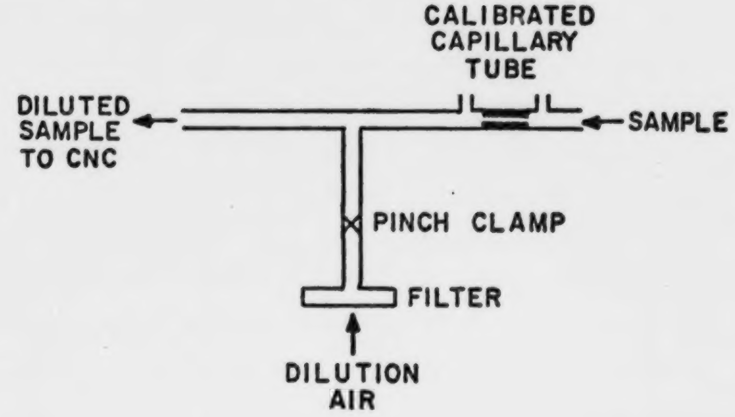

(b) AIR EJECTOR DILUTER
CALIBRATED ORIFICE
CALIBRATED ORIFICE
DILUTED SAMPLE
AIR EJECTOR
SAMPLE
FILTERED COMPRESSED AIR

Figure 9. Condensation nuclei counter system components

(c) CAPILLARY TUBE DILUTER


CALIBRATED
CAPILLARY
TUBE
DILUTED
SAMPLE
TO CNC
SAMPLE
PINCH CLAMP
FILTER
DILUTION
AIR

(d) LARGE PARTICLE REMOVER

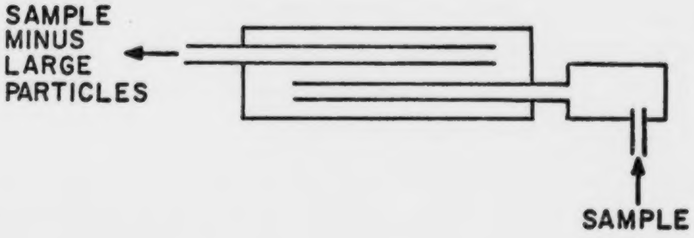

SAMPLE
MINUS
LARGE
PARTICLES
SAMPLE

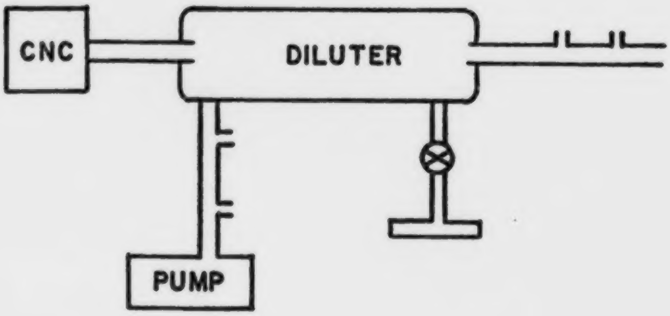
Figure 9. (continued). Condensation nuclei counter system components

The DD is made of three closely spaced (0.097 cm) concentric cylinders on which diffused particles are collected. The d_{50}, which is the particle diameter removed in the DD with 50 percent efficiency, is dependent upon the flow rate through the DD. For example, the d_{50} of the DD at flow rates of 60 cc/sec and 5 cc/sec are 0.013 μm and 0.050 μm respectively. The CNC is designed to respond to all particles 0.0025 μm and larger. Particle sizing is therefore determined by first sampling with the CNC without the DD, this concentration corresponds to particles $\geq$ 0.0025 μm. Next, the 60 cc/sec flow to the CNC is passed through the DD, where particles smaller than 0.013 μm are retained. Finally, a 5 cc/sec flow is passed through the DD, where particles smaller than 0.050 μm are retained. The capillary tube diluter allows a 5 cc/sec sample to be drawn through the DD with the remaining 55 cc/sec required by the CNC being made up of dilution air.

Figure 9d shows a large particle remover designed to provide a sample stream without any particles which could clog the system. The large particles are removed by impaction with a d_{50} of 15 μm for a flow of 240 cc/sec.

The initial outlet sampling configuration is shown in Figure 10a. This resulted in very low readings with the CNC (less than 1,000 particles/cc) which were believed to be caused by excessive dilution or particle losses in the diluter. Therefore, the diluter was removed and the flue gas drawn undiluted into the CNC. To protect the CNC from excessive temperatures and acid condensation, a condenser was used before the CNC. This also led to very low CNC readings which were probably due to the removal of condensation nuclei in the condenser. Later, it was found that the low CNC readings were caused by the low pressure of the sample entering the CNC from the pump diluter. The next setup utilized the capillary tube diluter after the probe. This also resulted in low CNC readings because the particles were probably removed as condensation formed in the tygon tubing between the diluter and the CNC. The condensation in the tygon tubing was due to insufficient dilution by the capillary tube

(a) ORIGINAL OUTLET SETUP


CNC
DILUTER
PUMP

(b) ORIGINAL INLET SETUP

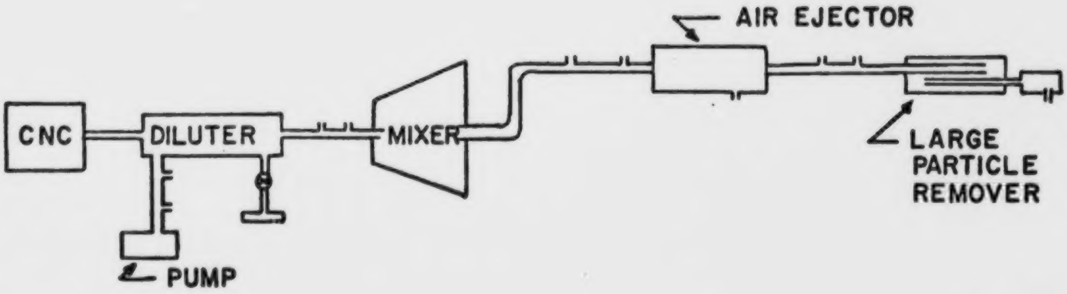
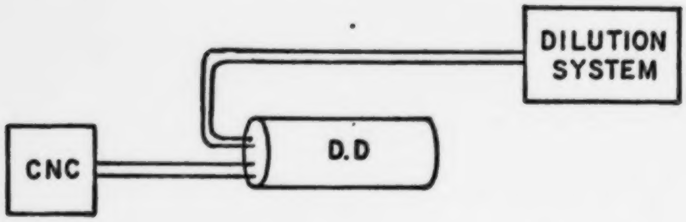

AIR EJECTOR
CNC
DILUTER
MIXER
LARGE PARTICLE REMOVER
PUMP

Figure 10. Condensation nuclei counter sampling configurations

(c) DIFFUSION DENUDER (D.D.) FLOW = CNC FLOW


DILUTION SYSTEM
CNC
D.D

(d) D.D. FLOW < CNC FLOW

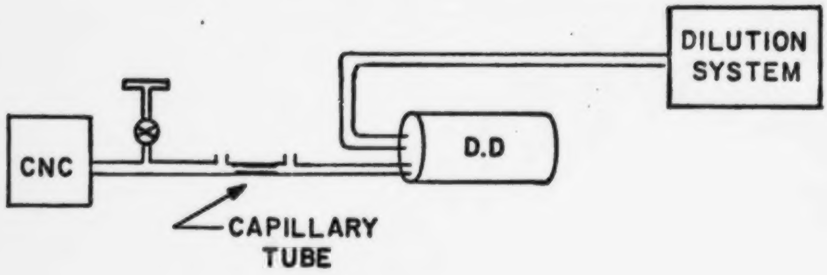

DILUTION SYSTEM
CNC
D.D
CAPILLARY TUBE

Figure 10. (continued). Condensation nuclei counter sampling configurations diluter. The final outlet sampling system consisted of the air ejector diluter preceded by the large particle remover. This system had the advantage of duplicating the final inlet sampling system. The initial inlet sampling system is shown in Figure 10b. A mixing chamber was used to provide a volume to which the air ejector diluter could discharge and from which the pump diluter could draw. The system was modified by removing the mixer and diluter due to low readings. The remaining inlet sampling configuration was utilized for the majority of the tests. A variation of the system was tried which included a condenser after the air ejector. This system proved inadequate due to a decrease in concentration with time which was apparently caused by removal of condensation nuclei in the condenser. The sampling systems used to provide various flow rates through the DD are shown in Figures 10c and 10d.

An accurate measurement of the particles in an effluent occurs only when there is proper sample extraction, treatment and measurement. Proper sample extraction is not a problem since the concentration of submicron particles is to be determined. These small particles are believed to be uniformly mixed in the effluent stream and are not affected by anisokinetic sampling. Proper sample treatment is a large factor in making an accurate measurement. The data has shown the effect of inadequate sample treatment in the losses due to condensation. Also, there have been indications of unwanted particle generation in the sampling system. Checking the dilution system in the field was performed by sampling ambient air through the diluters employed. However, this differs from actual sampling in that the sample's gaseous components and temperatures are not the same when sampling air, thereby introducing possible errors. Finally, proper measurement of the treated sample by the CNC was determined by periodically checking the CNC on the Zero and Test positions and by observing the CNC's response to an air sample. Even though the concentration of condensation nuclei in the atmosphere is variable, it generally read on the CNC's 100,000 and 300,000 scales. A quick response to a switch from effluent sampling to ambient sampling was interpreted to be an indication of proper CNC operation.

GASEOUS MEASUREMENTS

The sampling and analysis of stack gases was accomplished by the National Environmental Research Center, using its Mobile Flue Gas Analyzer. This van, shown in Figure 11, is instrumented to perform sampling and analysis of flue gases and in this case was used to determine the concentrations of carbon monoxide, carbon dioxide, sulfur dioxide, nitrous oxides, and oxygen.

Sampling procedures of the van provide for the extraction, by a carbon-vane vacuum pump, of stack gas from a sample port at a rate of approximately 1.5 scfm. Particulate is filtered out at the stack port. The sampled gases are maintained at stack temperature during its flow through the 200 feet of 1/2 inch Teflon tubing which extends from the sample port to the van. The sample tubing is spirally wrapped with heating wires covered with foam insulation and a polyvinyl-chloride jacket.

Before being introduced into the analyzer instruments, the sample gas is cooled and dried to approximately 32°F by successive passage through two refrigeration air driers, and the remaining particulates are removed with polishing filters.

The resultant gas stream of approximately 1 cfm is then compressed by a stainless steel diaphragm pump to 25 psig and directed to a manifold where it is distributed to each instrument through a matrix of stainless steel remote control valves which can also select span and zero gases for the calibration of each instrument. A set of in-line flow meters is used to monitor and control the gas flow as required by each instrument. Gases exhausted from the instruments are collected in a manifold and are then passed out of the van through Teflon tubing extending through the van floor to the atmosphere. The capabilities of the on-board analyzers are presented in Table 4. In addition to the instruments in Table 4, iron/constantan thermocouples measure the various gas temperatures with an accuracy of $\pm$ 2°F.

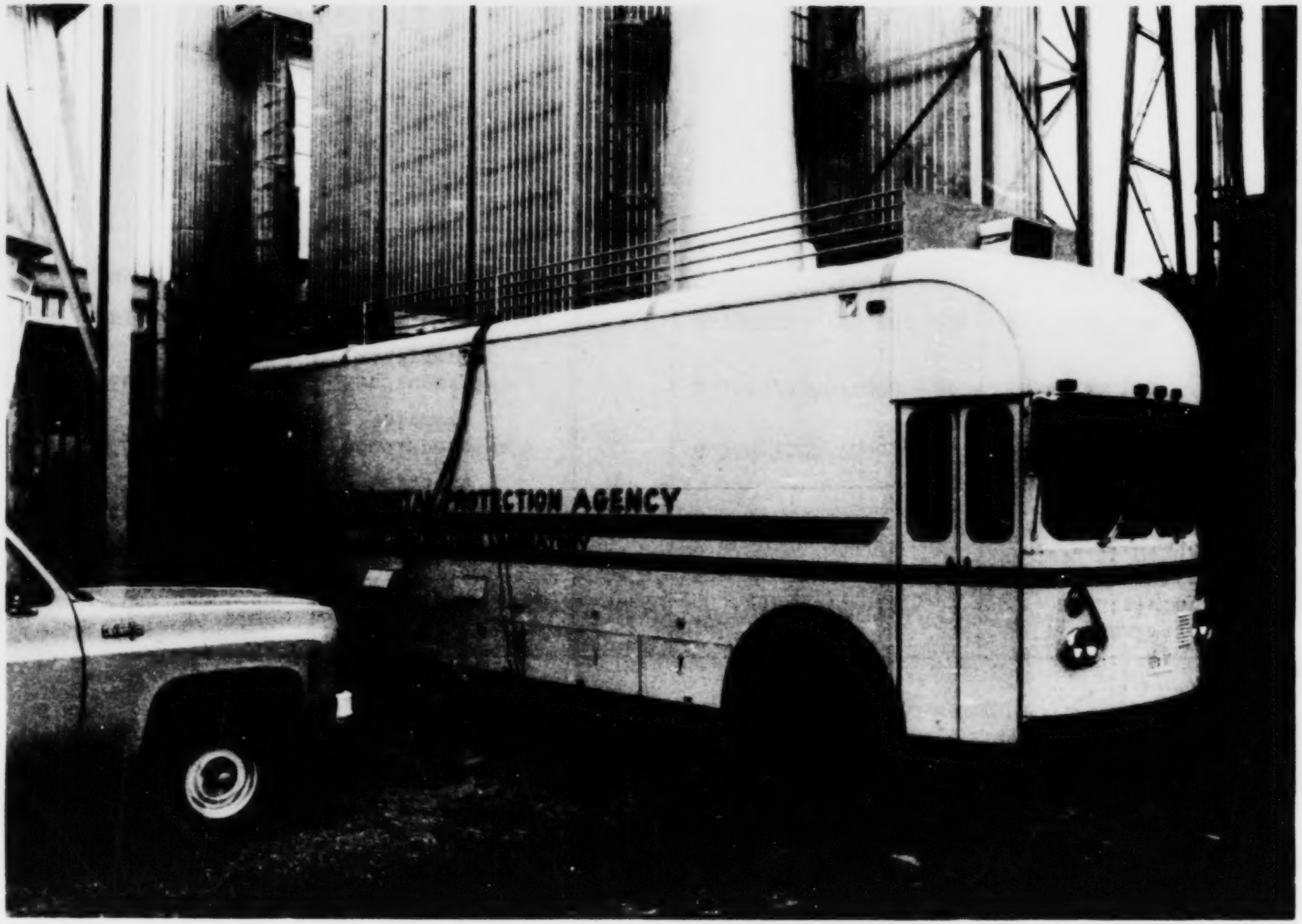

PROTECTION AGENCY

Figure 11. Mobile flue gas monitoring van

Table 4. CAPABILITIES OF THE MOBILE FLUE GAS ANALYZER'S INSTRUMENTATION

Gas component	Type of analysis	Range	Range levels	Approximate sensitivity
Oxygen	Polargraphic	4	0.1/5/10/25%	0.01/0.05/0.10/0.25%
Carbon dioxide	Nondispersive infrared	3	0-5/10/20%	0.05/0.1/0.2%
Carbon monoxide	Nondispersive infrared	3	0-500/1000/2000 ppm	5/10/20 ppm
Sulfur dioxide	Nondispersive infrared	3	0-1000/2000/4000 ppm	10/20/40 ppm
Nitrous oxides	Chemiluminescent	3	0-200/2000/20,000 ppm	2/20/200 ppm
Hydrocarbon	Flame ionization	5	0-4/40/400/4000/ 40,000 ppm	0.04/0.4/4/ 40/400 ppm

SECTION VI

RESULTS

A total of 22 tests were run at the Nucla facility with the field effort divided into two phases. Tests 1 through 16 were performed over the period of September 21, 1974 through October 7, 1974. The remaining tests, 17 through 22, were completed between October 22, 1974 and October 27, 1974.

Eleven of the 22 tests were run under normal baghouse operating conditions with the remaining tests made under special experimental conditions. The baghouse operating conditions and the inlet and outlet mass loadings for the tests are shown in Table 5. The mass efficiency was calculated using the inlet and outlet Method 5 mass loadings. The outlet mass loading for run 22 was not obtained and therefore no mass efficiency was determined but the particle sizing information from that run was included in the sizing analysis.

The mean mass efficiency for all runs was 99.84 percent with a standard deviation of 0.11. The results of two particular tests are noteworthy, however. Run number eight resulted in a mass efficiency of over 99.98 percent, the highest reported for all runs. This high collection efficiency is explained by the very high inlet loading observed that day. The boiler was experiencing some very poor combustion conditions for part of the run and the problem must be attributed to the combustion system rather than the fuel because the coal properties did not appear to be atypical on that day. The observation that the baghouse could operate

Table 5. RESULTS OF PARTICULATE SAMPLING AT NUCLA

Date	Run	Inlet mass loading grains/dscf			Outlet mass loading grains/dscf			Mass efficiency (percent)	Baghouse operation
		Method 5	Andersen A	Andersen B	Method 5	Andersen north	Andersen west		
9/21/74	1	2.0759	0.4984	-	0.0044	0.0101	0.0031	99.7880	Normal
9/22/74	2	2.1712	1.5078	1.4610	0.0049	0.0069	0.0034	99.7743	Normal
9/23/74	3	1.9753	1.4014	1.7176	0.0045	0.0034	0.0028	99.7722	Normal
9/24/74	4	1.7021	1.7092	1.1793	0.0063	0.0043	0.0021	99.6299	Normal
9/25/74	5	1.6768	1.4819	1.4382	0.0042	0.0031	0.0030	99.7495	Cont. cleaning
9/26/74	6	1.7995	1.3426	1.1600	0.0047	0.0048	0.0051	99.7388	Cont. cleaning
9/27/74	7	1.8516	1.3144	1.9251	0.0045	0.0033	0.0025	99.7570	Normal
9/28/74	8	11.4446	1.6248	2.0818	0.0016	0.0053	0.0015	99.9860	Long repressure
9/30/74	9	2.3878	1.6636	1.9608	0.0016	0.0021	0.0020	99.9330	Long repressure
10/1/74	10	1.6873	1.4206	1.3540	0.0010	0.0021	0.0034	99.9407	Normal
10/2/74	11	1.7422	1.0294	1.4893	0.0015	0.0035	0.0046	99.9139	No cleaning
10/3/74	12	2.1112	1.5900	1.3091	0.0092	0.0563	0.0796	99.5642	No cleaning
10/4/74	13	2.2693	1.8991	2.0574	0.0040	0.0034	0.0035	99.8237	Normal
10/5/74	14	1.7751	1.6593	1.4318	0.0029	0.0047	0.0154	99.8366	No repressure
10/6/74	15	1.3572	2.4579	1.6854	0.0007	0.0039	0.0036	99.9484	No repressure
10/7/74	16	2.1779	2.3232	1.5909	0.0019	0.0042	0.0037	99.9128	Normal
10/22/74	17	2.1098	1.8337	-	0.0022	0.0025	0.0025	99.8957	Normal
10/23/74	18	2.0669	1.5351	1.6651	0.0010	0.0024	0.0022	99.9516	Long repressure
10/24/74	19	1.9828	1.8120	1.7094	0.0015	0.0030	0.0021	99.9244	Normal
10/25/74	20	1.7791	2.9943	1.6683	0.0017	0.0025	0.0025	99.9045	No shaking
10/26/74	21	1.9502	1.5053	1.3352	0.0015	0.0028	0.0023	99.9231	No shaking
10/27/74	22	2.0572	1.9528	1.7008	-	0.0036	0.0035	-	Normal

under such adverse conditions and still allow a penetration of only 0.0016 grains/dscf is important.

The results of run number 12 are also interesting in that the lowest efficiency and highest outlet loading of all tests were observed during that test. It also is a day on which seven bags were replaced in the baghouse so that one might expect the performance to improve with the removal of failed bags. It was learned, however, that the bags that were replaced during run 12 were in particularly bad shape with some bags having tears several feet long. This resulted in a large amount of fly ash being deposited on the floor of the baghouse. When the bags were replaced the fly ash was not removed and it is theorized that when that compartment came back on line the fly ash was gradually reentrained and swept up the stack resulting in the extraordinarily high outlet concentration.

The cascade impactor results showed a mean mass median diameter at the inlet of 18.4 μm with a standard deviation of 5.2 while at the outlet of the baghouse the mean mass median diameter was 8.8 μm with a standard deviation of 4.1. A summary of the mass median diameter data is shown in Table 6. The particle size distribution curves generated from the impactor data show day to day variations but no significant trends or correlations could be ascribed to the scatter. The particle size distribution curves are presented in Appendix A. The utilization of two identical Andersen impactors side by side at the outlet sampling location for all 22 tests affords an opportunity to examine the precision of the technique. As can be seen from Table 7, the geometric mean concentrations as measured by each impactor are very close to each other. However, the average absolute value of the difference of each paired measurement is about 70 percent of the overall geometric mean. This means that with any given paired sample, a significant difference is quite apt to be observed between the individual impactors. If one does not take the absolute value of the difference, however, the average difference is only about 18 percent of the geometric mean of all measurements. This shows that one impactor does not always tend to be biased, and that the differences, though large, are probably random.

Table 6. RESULTS OF PARTICLE SIZING AT NUCLA

Date	Inlet		Outlet	
	Andersen A, mmd, μm	Andersen B, mmd, μm	Andersen north mmd, μm	Andersen west mmd, μm
9/21/74	37	-	10.8	12.9
9/22/74	17.6	28	8.8	21
9/23/74	21	20.5	18.1	13.5
9/24/74	16.5	21.5	14.9	9.4
9/25/74	20	23.4	15.3	8.0
9/26/74	16.5	20.8	10.1	11.0
9/27/74	17.1	18.3	8.6	9.5
9/28/74	16.2	15.5	-	4.55
9/30/74	18.2	11.6	9.7	4.45
10/1/74	19.0	15.5	6.1	13.4
10/2/74	16.5	16.0	7.2	7.6
10/3/74	18.1	14.2	0.80	-
10/4/74	12.5	27	14.6	7.0
10/5/74	18.6	20.7	10.2	-
10/6/74	1.2	16.0	9.5	8.7
10/7/74	21.0	16.0	7.7	6.3
10/22/74	17.3	-	4.1	6.2
10/23/74	18.8	15.3	7.0	5.4
10/24/74	15.8	17.2	4.4	5.2
10/25/74	-	18.0	6.3	5.5
10/26/74	22.0	18.0	5.8	5.4
10/27/74	19.5	21.7	7.4	7.4

Table 7. COMPARISON OF OUTLET IMPACTOR RESULTS

	Geometric mean concentration, grains/dscf	Geometric standard deviation
Impactor X	0.0041	2.0085
Impactor Y	0.0036	2.2982
Impactor X + Y	0.0038	2.1419

$$\frac{\Sigma\, |X - Y|}{n} = 0.0026 \qquad \frac{\Sigma\, (X - Y)}{n} = -0.0007$$

	Geometric mean mass median diameter, μm	Geometric standard deviation
Impactor X	8.57	1.51
Impactor Y	8.13	1.50
Impactor X + Y	8.34	1.50

$$\frac{\Sigma\, |X - Y|}{n} = 3.26 \qquad \frac{\Sigma\, (X - Y)}{n} = 0.45$$

A similar analysis of the mass median diameter as determined by each impactor shows the same trend but the geometric standard deviations are somewhat smaller. Further, the average absolute value of the difference of each paired measurement is only about 40 percent of the overall geometric mean. The average difference of each pair, not taking the absolute value, is only about 5 percent of the geometric mean. It would appear, therefore, that substantial, apparently random differences are quite apt to be observed in the mass median diameters as determined bv paired impactors but that those differences are less than those observed for the measured mass concentration.

The fractional efficiency for each run was calculated from differential size distribution plots, which are contained in Appendix B. The differential particle size distributions were constructed in the manner described by Smith et al.[1] The concentration of each of six particle diameters was averaged for the two impactor runs at the inlet and outlet and the efficiency calculated for each size. These fractional efficiency, or fractional penetration, curves show the performance of the baghouse as a function of particle size. The results of all 22 fractional efficiency curves which are presented in Appendix C have been combined in Figure 12 to give the median efficiency/penetration over the range of 1 to 10 μm. The result is a fairly smooth curve that tends toward higher collection efficiencies for the larger particles and toward higher penetration for the smaller particle sizes. Also shown in Figure 12 is the range of observed efficiency/penetration values for each size, but excluding the extreme observation (highest and lowest). The wider bar indicates the range of that half of the values nearest the median while the thinner bar indicates the range of that half of the values furthest from the median.

The measurements made with condensation nuclei counter system are presented in Appendix D. All of the CNC measurements were evaluated in terms of the static pressure at the instrument inlet, indications of condensation having taken place and whether the readings appeared to be reasonably stable for a nominal 5 minutes with no wild fluctuations. This exercise cast doubt on more than 90 percent of the 200 measurements. Those measurements that withstood the scrutiny are shown in Table 8 and are the basis for the size distributions at the baghouse inlet as shown in Figures 13 and 14. These two figures show count median diameters of 0.015 and 0.020 μm. It is not known why the number concentration on October 27 was so much higher than on October 26 but the effect is thought to be real. Indeed the mass concentration of the smaller particles as measured by the Andersen back-up filters was more than twice as high on October 27 as on October 26.

The mean of all the inlet readings from Table 8, except those in which the DD was used, is 18 million particles/cc. Since there are only two outlet readings in Table 8 and those readings vary by such a large amount, a reading was selected. The 27 October 1974 reading at 1738

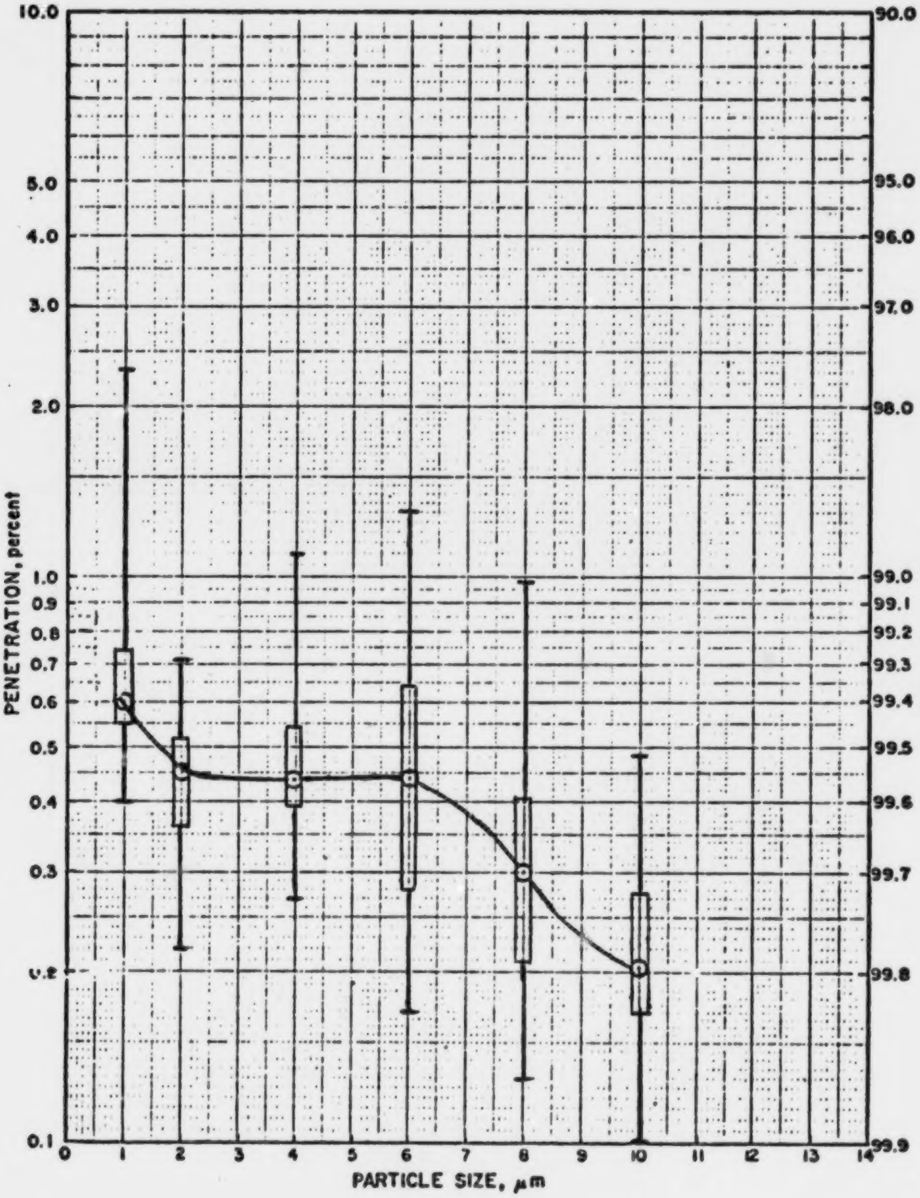


Figure 12. Median fractional efficiency for 22 tests

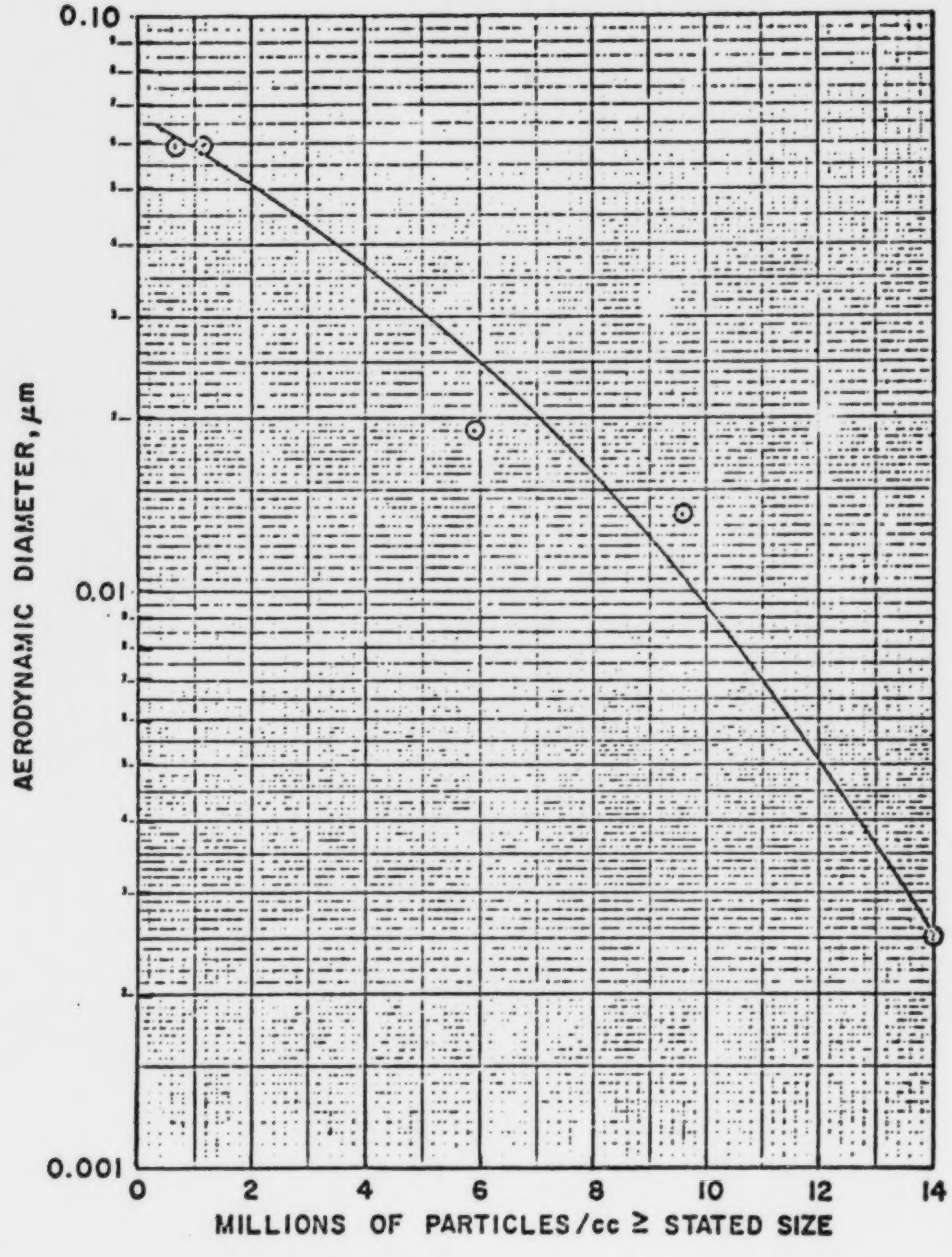


Figure 13. Inlet condensation nuclei counter sizing measurements (10/26/74)

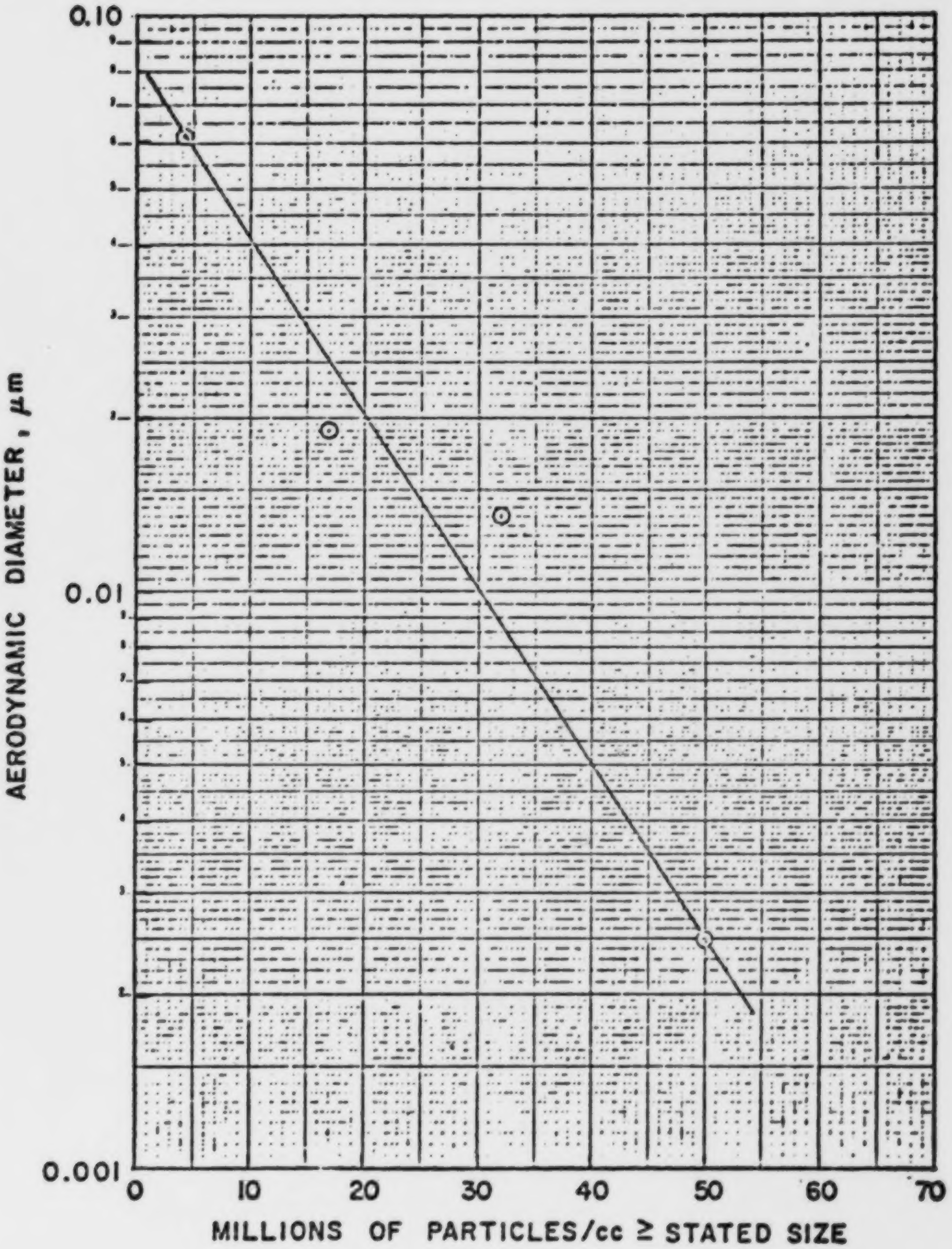


Figure 14. Inlet condensation nuclei counter sizing measurements (10/27/74)

Table 8. SUMMARY OF ACCEPTABLE CNC MEASUREMENTS

Date	Time	Inlet concentration, particles/cc	Diffusion denuder d_{50}, μm	Outlet concentration, particles/cc	Diffusion denuder d_{50}, μm
9/26/74				4,300,000	
9/30/74		6,100,000			
		7,000,000			
10/1/74		3,800,000			
		3,500,000			
10/2/74	1525	3,600,000			
	1645	25,000,000			
	1720	27,000,000	0.0125		
	1723	27,000,000			
10/26/74	0920	12,000,000			
	0940	14,000,000			
	0956	9,400,000			
	1027	16,000,000			
	1045	14,000,000			
	1102	9,600,000	0.0135		
	1135	5,600,000	0.0190		
	1142	1,200,000	0.0590		
	1150	710,000	0.0590		
10/27/74	1325	31,000,000			
	1347	35,000,000			
	1422	50,000,000			
	1441	32,000,000	0.0135		
	1459	17,000,000	0.0190		
	1530	4,400,000	0.0610		
	1549	4,500,000	0.0610		
	1738			49,000	
	1800			0	0.0140

was chosen because the dilution system used duplicates the dilution system used for all the acceptable inlet readings. If the mean inlet reading and the 27 October 1974 outlet reading are used, the removal efficiency of the baghouse for particles in the 0.0025 μm to 0.5 μm range is 99.74 percent. This, combined with the results of the impactor measurements, would indicate a collection efficiency greater than 99 percent on a mass basis down to about 1 μm, and similarly, a collection efficiency greater than 99 percent on a number basis for particles between about 0.5 μm and 0.0025 μm.

In addition to the particulate measurements that were made, several uncontrollable variables were monitored throughout the tests so that their effects, if any, could be examined. These variables included the ash, moisture and sulfur content of the coal, the boiler steam load and baghouse parameters, such as the number of cleaning cycles during each test and the occurrence of bag failures. A summary of the daily values of the uncontrollable variables is presented in Table 9. The measured and calculated properties of the inlet and outlet flue gases are summarized in Table 10.

An attempt was made to keep the boiler load steady but day to day differences in demand and in operating conditions resulted in some fluctuations. The mean boiler load for all tests was 111,000 pounds of steam per hour with a standard deviation of 8,500. There was no control over the properties of the coal that was burned; therefore, three coal samples were taken from the boiler feed each day and analyzed for heating value and composition. The complete coal analyses are contained in Appendix E. The daily average ash content ranged from 11.38 percent to 18.00 percent with a mean value of 14.34. The daily average sulfur content ranged from 0.60 percent to 1.72 percent with a mean of 0.78 while the average heating value ranged from 11,798 to 12,978 with a mean of 12,423 Btu per pound.

Table 9. SUMMARY OF MONITORED UNCONTROLLABLE VARIABLES

Date	Avg. % ash	Avg. % moisture	Avg. % sulfur	Avg. boiler steam load 1000 lbs/hr	No. of cleaning cycles	No. of bags replaced
9/21/74	14.59	7.95	0.72	115	2	-
9/22/74	14.66	7.97	0.73	99	1	-
9/23/74	13.50	5.99	0.82	112	7	-
9/24/74	11.38	5.67	1.11	113	1	-
9/25/74	13.09	6.47	1.72	117	14	-
9/26/74	12.89	6.50	0.90	117	14	-
9/27/74	13.89	5.64	0.67	116	5	6
9/28/74	14.19	6.34	0.72	117	14	-
9/30/74	14.36	5.93	0.75	117	3	-
10/01/74	18.00	6.54	0.60	101	5	-
10/02/74	15.58	7.44	0.68	96	0	-
10/03/74	13.88	6.83	0.66	118	0	7
10/04/74	14.23	5.77	0.64	117	5	5
10/05/74	13.62	6.28	0.63	118	11	-
10/06/74	13.60	4.96	0.69	85	1	-
10/07/74	15.24	6.92	0.85	117	3	-
10/22/74	15.48	8.42	0.68	114	4	-
10/23/74	16.56	9.01	0.80	111	2	-
10/24/74	12.27	8.71	0.68	111	3	-
10/25/74	15.00	7.18	0.65	111	12	-
10/26/74	14.11	8.08	0.75	110	14	-
10/27/74	14.17	8.37	0.75	111	7	-

Table 10. FLUE GAS PROPERTIES

Date	Inlet						Outlet							
	Moisture, %	CO_2, %	O_2, %	CO, %	Stack temperature, °F	Volumetric flow rate, acfm	Moisture, %	CO_2, %	O_2, %	CO, %	Stack temperature, °F	Volumetric flow rate, acfm	Concentration, lbs/10^2 Btu	lbs part/hr
9/21/74	7.64				283	44,434	6.24				250	40,300	0.0106	1.53
9/22/74	7.26				275	39,595	5.69				246	41,731	0.0137	1.76
9/23/74	4.83				281	41,513	5.63				254	41,489	0.0111	1.61
9/24/74	7.13				283	41,946	5.66		7.6	0.0	248	41,644	0.0145	2.26
9/25/74	7.32				281	42,694	5.87		8.0	0.0	252	43,351	0.0106	1.54
9/26/74	7.46				276	40,746	6.03		6.8	0.0	252	37,635	0.0102	1.52
9/27/74	6.65				276	43,426	4.67		7.4	0.0	240	40,194	0.0104	1.54
9/28/74	6.87		6.0	0.0	267	44,000	5.38		9.2	0.0	243	38,480	0.0036	0.52
9/30/74	6.21		5.2	0.0	266	42,295	5.12		7.4	0.0	246	38,544	0.0036	0.54
10/1/74	3.77		7.3	0.0	267	41,793	5.12		7.7	0.0	238	37,618	0.0025	0.326
10/2/74	5.40				270	47,670	3.75		6.7	0.0	247	42,292	0.0043	0.53
10/3/74	6.37		6.1	0.0	280	41,008	5.87		8.1	0.0	249	39,717	0.0211	2.12
10/4/74	7.15				272	44,179	5.84		6.9	0.0	246	39,240	0.0092	1.36
10/5/74	7.12				273	48,681	5.43		7.6	0.0	239	40,120	0.0060	0.98
10/6/74	6.03	-	8.4	0.0	259	39,876	4.08		4.5	0.0	233	37,487	0.0020	0.228
10/7/74	6.86				271	46,483	5.07		8.4	0.0	245	41,711	0.0046	0.665
10/22/74	7.33	11.8	7.0	0.8	256	48,803	5.78	11.0	8.0	1.0	240	42,907	0.0055	0.823
10/23/74	4.92	12.9	6.6	0.5	261	47,580	6.50	12.0	7.6	0.0	242	39,479	0.0024	0.34
10/24/74	7.07	11.9	7.2	0.4	266	44,711	5.67	10.5	8.5	0.2	238	40,312	0.0034	0.50
10/25/74	6.63	10.0	9.0	0.4	264	45,162	5.32	11.5	8.1	0	234	41,058	0.0042	0.605
10/26/74	5.44	12.0	6.9	0.0	271	45,718	5.56	9.6	8.6	0	233	41,034	0.0036	0.524
10/27/74	6.39	11.5	7.0	0.4	266	44,750		10.8	8.9	0.5				

Analysis of selected coal and fly ash samples were made for trace elements using atomic absorption. The results of these analyses are presented in Table 11. Along with the analysis by AA, some samples were examined using a scanning electron microscope and X-ray fluorescence. The X-ray spectra and photomicrographs at three magnifications of one of the fly ash samples are shown in Figures 15, 16, 17, and 18. The elemental analyses for the coal and fly ash samples examined by X-ray fluorescence are shown in Table 12.

A multiple regression analysis was employed to determine the effect of the most obvious variables on particulate penetration. The list of variables analyzed and the correlation matrix is shown in Table 13. Most of the variables are self-explanatory except those associated with the baghouse operation. Variable 6, the number of shakes per cycle, was varied only for tests 20 and 21 when the shaking part of the cleaning cycle was eliminated. Variable 7 is a somewhat qualitative assignment that attempts to account for the excessive frequency of bag failures that were experienced. The baghouse was inspected periodically for broken bags and nearly every inspection resulted in bag replacement. Since it was impossible to determine when the bag failure had actually occurred, each day was assigned the number equal to the number of days since a baghouse inspection that resulted in bag replacement.

Variable 9, the length of reverse flow, was normally 15 seconds. In three tests it was extended to 60 seconds and in two tests it was eliminated. Variable 10, the number of cleaning cycles during the test, was included because there usually was little control over the frequency of cleaning. The cleaning cycle is actuated when the pressure drop across the bag reaches 4 inches of water and hence was dependent upon the quality of the coal, the quality of combustion in the boiler, the flue gas flow rate, etc. In addition two tests were run in which the pressure transducer was bypassed so that no cleaning took place which resulted in each compartment being active for the entire 6 hour sampling period.

Table 11. ANALYSIS OF SELECTED COAL AND FLY ASH SAMPLES FROM BOILER No. 2

	Coal samples			Fly ash samples		
	0855 9/28/74	0900 10/01/74	1155 10/25/74	Compartment #4 hopper 1230 10/25/74	Compartment #5 hopper 1235 10/25/74	Compartment #6 hopper 1240 10/25/74
% Ash	12.40	14.72	12.81	-	-	-
Ash analysis						
% Loss on ignition	-	-	-	32.53	35.61	39.65
% Moisture	-	-	-	0.45	0.48	0.45
% Silica (SiO_2)	52.56	50.28	51.04	31.87	31.00	28.79
% Iron oxide (Fe_2O_3)	9.30	13.10	8.50	9.65	12.53	5.33
% Aluminum oxide (Al_2O_3)	30.50	26.20	33.50	19.10	14.40	19.76
% Calcium oxide (CaO)	1.20	5.56	3.52	3.22	4.60	3.71
% Titanium oxide (TiO_2)	2.00	1.60	1.60	1.07	1.02	0.96
% Potassium oxide (K_2O)	0.92	0.80	0.76	0.18	0.15	0.14
% Sodium oxide (Na_2O)	0.19	0.19	0.19	0.20	0.10	0.11

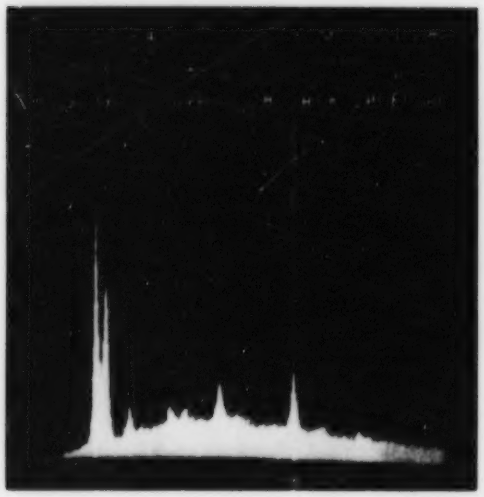


Figure 15. Fly ash from baghouse hopper number 4, October 25, 1974; X-ray fluorescence spectra

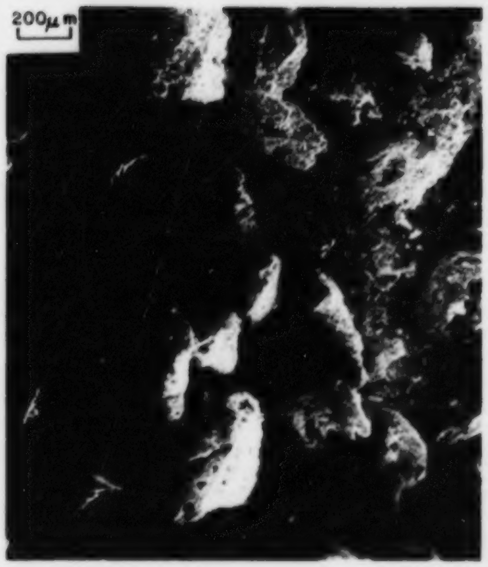


Figure 16. Fly ash from baghouse hopper number 4, October 25, 1974; scanning electron micrograph, 50 magnification at 10 kV

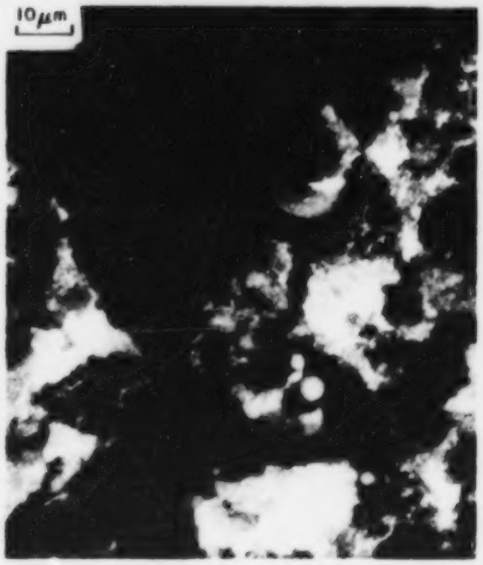


Figure 17. Fly ash from baghouse hopper number 4, October 25, 1974; scanning electron micrograph, 1000 magnification at 30 kV

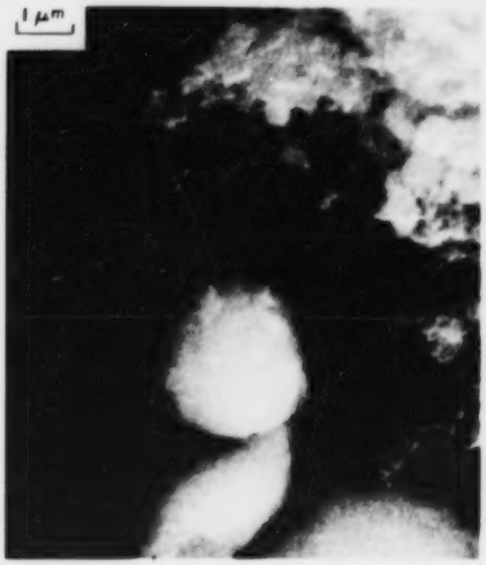


Figure 18. Fly ash from baghouse hopper number 4, October 25, 1974; scanning electron micrograph, 10,000 magnification at 30 kV

Table 12. RESULTS OF X-RAY FLUORESCENCE ANALYSIS OF COAL AND FLY ASH

			Elements in order of concentration								
	Date	Time	Max conc → Min conc								
Coal	10/22	1450	Si	Al	S	Fe	Ti	K	Ca		
	10/25	0905	Si	Al	S	Fe	K	Ca	Cr (trace)		
	10/25	1445	Si	Al	S	Fe	Ti	K	Ca		
	10/26	1115	Si	Al	S	Fe	K	Ca			
	10/26	1520	Fe	Si	Al	S	K	Ca	Ti		
Fly ash	10/22	1530	Si	Al	S	Fe	Ti	Ca	K	Cl	Mn
	10/22	1535	Si	Al	S	Fe	Ti	Ca	K		
	10/22	1540	Al	Si	S	Ca	Cl	Fe	Ti		
Fly ash	10/25	1230	Al	Si	Fe	Ti	S	K	Ca	Cu	
	10/25	1235	Al	Si	S	Ti	Fe	Cu			
	10/25	1240	Si	Al	S	Ti	Fe	Ca			
Fly ash	10/26	1445	Al	Si	S	Ti	Fe	Ca			
	10/26	1450	Si	Al	S	Ca	Ti	Fe (trace)			
	10/26	1455	Si	Al	S	Fe	Ca	Ti	K		
	10/26	1500	Si	Al	Fe	Ti	K	Ca	S	Cl	Mn
	10/26	1505	Si	Al	S	Fe	K	Ca	Ti	Cl	
	10/26	1510	Si	Al	S	Ca	Ti	Fe	K	Cl	

Table 13. CORRELATION MATRIX FOR TESTS 1 TO 21

Run	Variable	1	2	3	4	5	6	7	8	9	10	11	12
1	Inlet, gr/ft^3	1.000	-0.144	-0.070	-0.004	-0.086	0.083	-0.238	0.215	0.703	0.319	0.291	-0.290
2	Outlet, gr/ft^3		1.000	-0.214	-0.307	0.233	0.238	-0.369	0.382	-0.155	-0.149	-0.975	0.975
3	Coal moisture, percent			1.000	0.404	-0.133	-0.221	0.472	0.028	-0.090	-0.115	0.250	-0.250
4	Coal ash, percent				1.000	-0.423	-0.052	0.000	-0.268	0.040	-0.202	0.558	-0.558
5	Coal sulfur, percent					1.000	0.114	0.283	0.222	-0.009	0.276	-0.333	0.333
6	Bag shakes per cleaning cycle						1.000	-0.608	0.021	0.065	-0.442	-0.214	0.214
7	Days since baghouse inspection							1.000	-0.100	-0.146	0.347	0.261	-0.261
8	Boiler steam load, 1000 lb/hr								1.000	0.321	0.390	-0.332	0.332
9	Repressure time, seconds									1.000	0.118	0.275	-0.275
10	Cleaning cycles per test										1.000	0.128	-0.128
11	Efficiency percent											1.000	-1.000
12	Penetration, percent												1.000

In two other tests the baghouse was forced to clean continuously which resulted in a total of 14 cleaning cycles during the test period and each compartment being active only 5 of the 6 hours of testing.

Equation 1, constructed from the 11 tests with normal baghouse operating parameters, explains 95.3 percent of the variance in penetration.

$$\text{percent penetration} = 1.169 + 10^{-2} \Big[-3.62\ (\text{coal ash, \%}) - 3.76\ (\text{days since inspection}) + 31.81\ (\text{coal sulfur, \%}) - 0.40\ (\text{steam load}) - 13.14\ (\text{inlet grain loading}) + 1.45\ (\text{coal moisture, \%})\Big] \qquad (1)$$

The regression analysis for all 21 tests, that is for normal and abnormal baghouse operating conditions combined, results in a substantial reduction in the predictability of penetration, although 62.7 percent of the variance in penetration is still explained by equation (2).

$$\text{percent penetration} = 0.367 + 10^{-2} \Big[-3.75\ (\text{coal ash, \%}) - 1.70\ (\text{inlet grain loading}) - 2.64\ (\text{days since inspection}) + 0.28\ (\text{steam load}) + 11.70\ (\text{coal sulfur, \%}) - 0.12\ (\text{repressure time}) + 1.66\ (\text{coal moisture, \%}) - 0.40\ (\text{shakes per cleaning cycle})\Big] \qquad (2)$$

Notable in equation (2) is the apparently slight influence of the deliberately altered variables. Several changes were made in the cleaning cycle that were expected to significantly effect performance. These variables, however, either do not appear in the penetration equation or appear as only slight influences on penetration. To test this observation the mean penetration was computed for the 11 tests under normal operating conditions and for each series of tests under experimental baghouse operating conditions. Comparison by a two-sample t-test reveals that for all situations, except increased duration of reverse air during cleaning (variable 9), one would fail to reject at the 0.10 level the null hypothesis that the means are equal. That is, all abnormal conditions except increased reverse air duration do not show statistically significant differences in the penetration as compared to normal conditions.

The first of the tests in which the reverse air was increased to 60 seconds coincided with an inlet particulate concentration more than five times higher than during any other run. During that test it was noted that an extended period of very poor combustion occurred in the boiler which probably caused the extremely high particulate loading. Because of this observation the increased time of reverse air flow was repeated for test 9 and again for test 18. When the results of only tests 9 and 18 are compared with the results of the normal tests, the difference in penetration is no longer statistically significant. It certainly appears that the results obtained by including test 8 are more dependent on the high inlet loading caused by the boiler misfire than on the increase in the duration of reverse air flow.

REFERENCE

1. Smith, W. B., K. M. Cushing, and J. D. McCain. Particulate Sizing Techniques for Control Device Evaluation. Southern Research Institute. EPA-650/2-74-102. October 1974.

APPENDIX A

PARTICLE SIZE DISTRIBUTION CURVES

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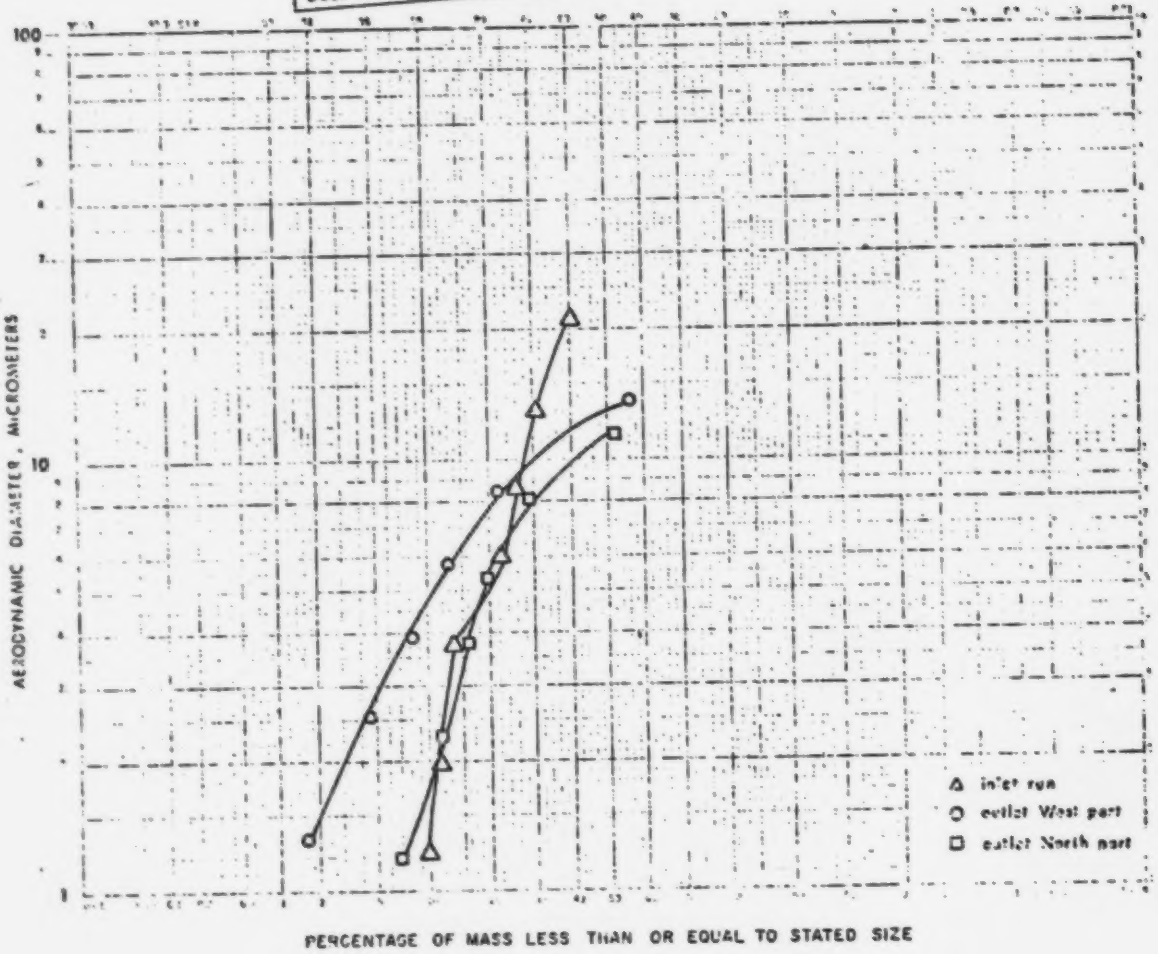

Figure 19. Cumulative particle size distributions determined by Andersen Impactors for Run 1

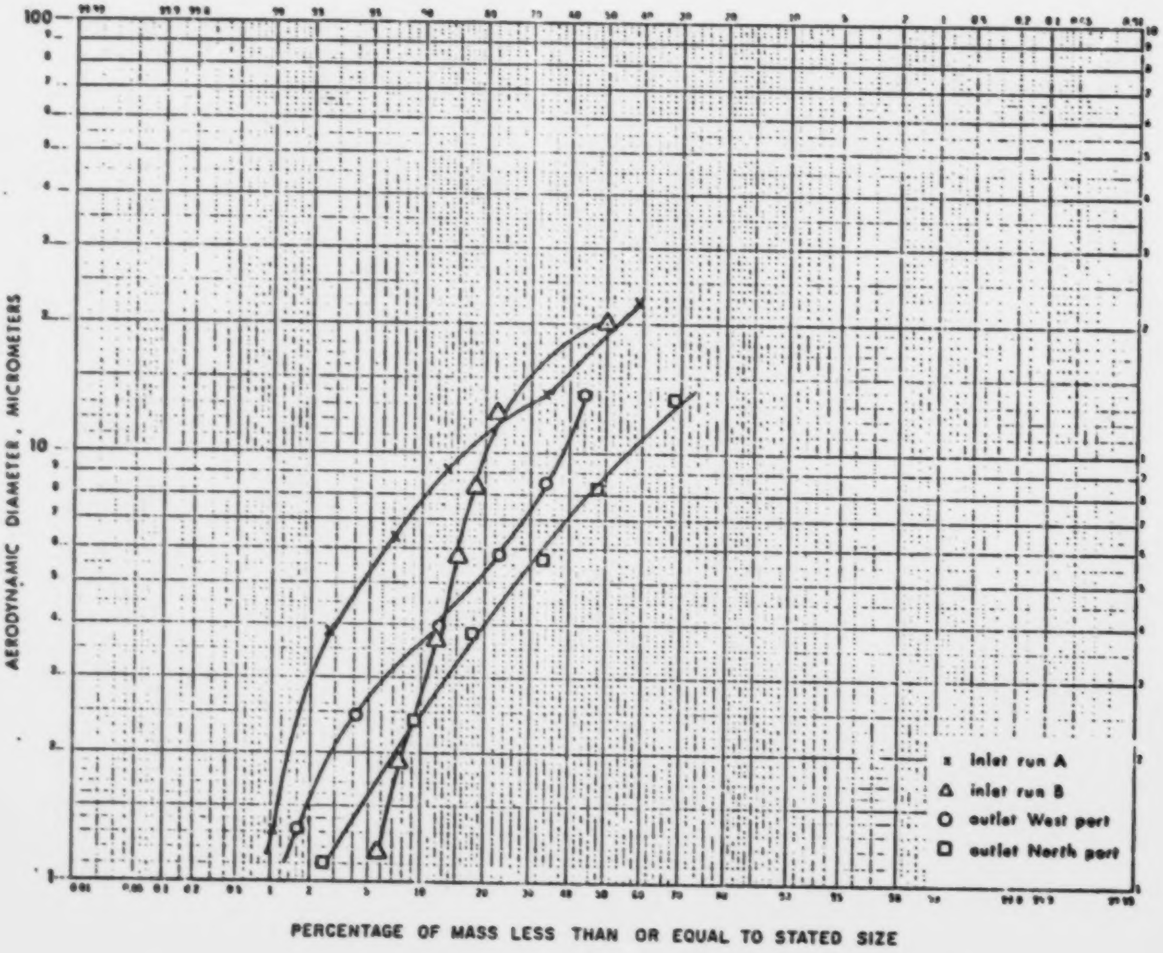

Figure 20. Cumulative particle size distributions determined by Andersen Impactors for Run 2

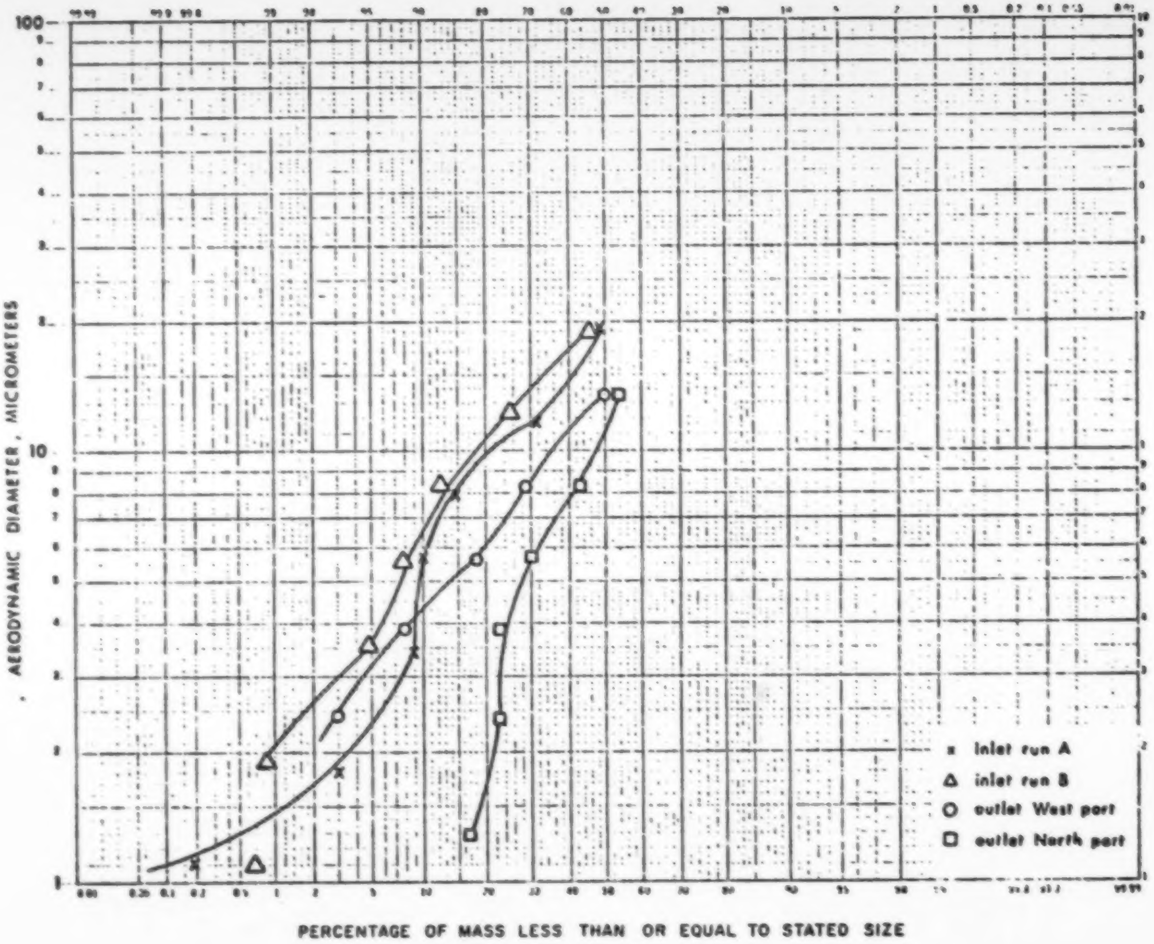

Figure 21. Cumulative particle size distributions determined by Andersen Impactors for Run 3

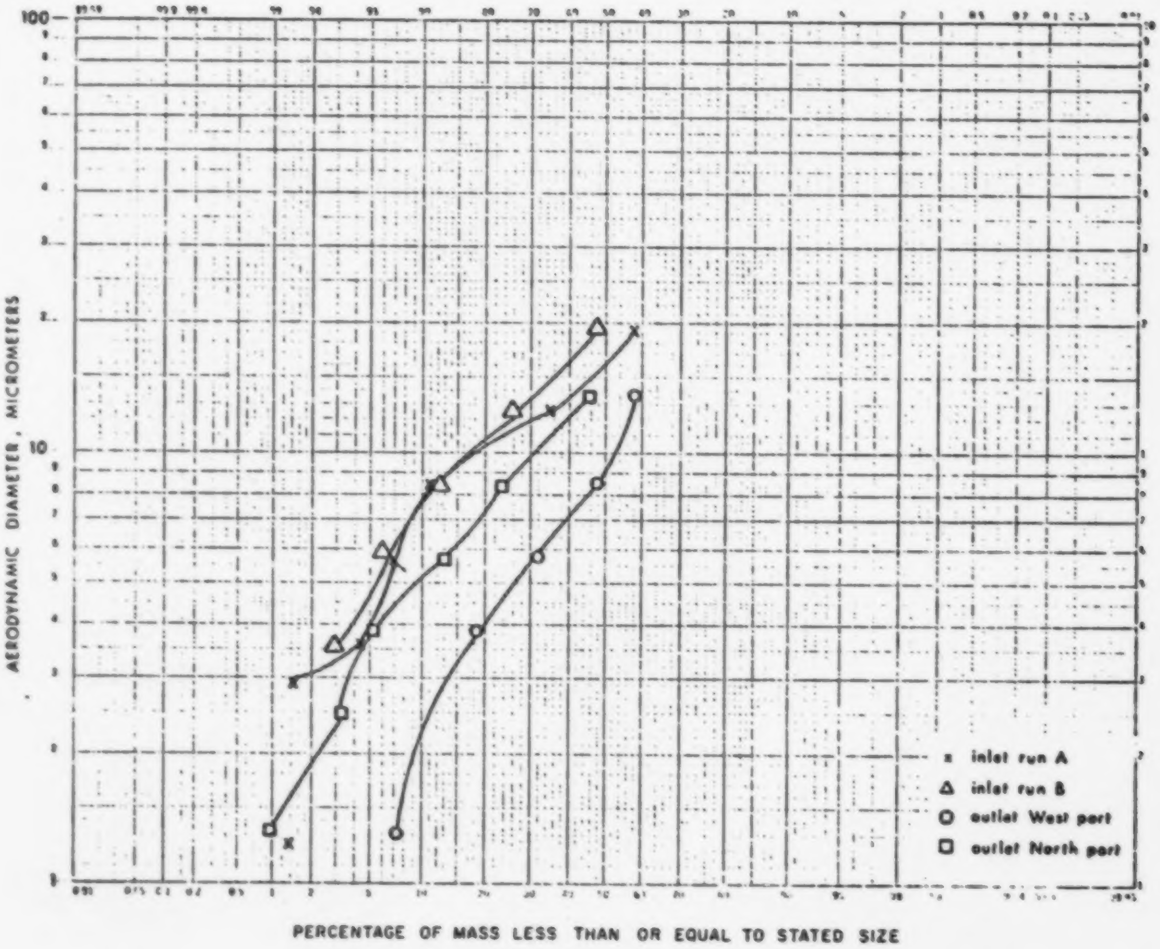

Figure 22. Cumulative particle size distributions determined by Andersen Impactors for Run 4

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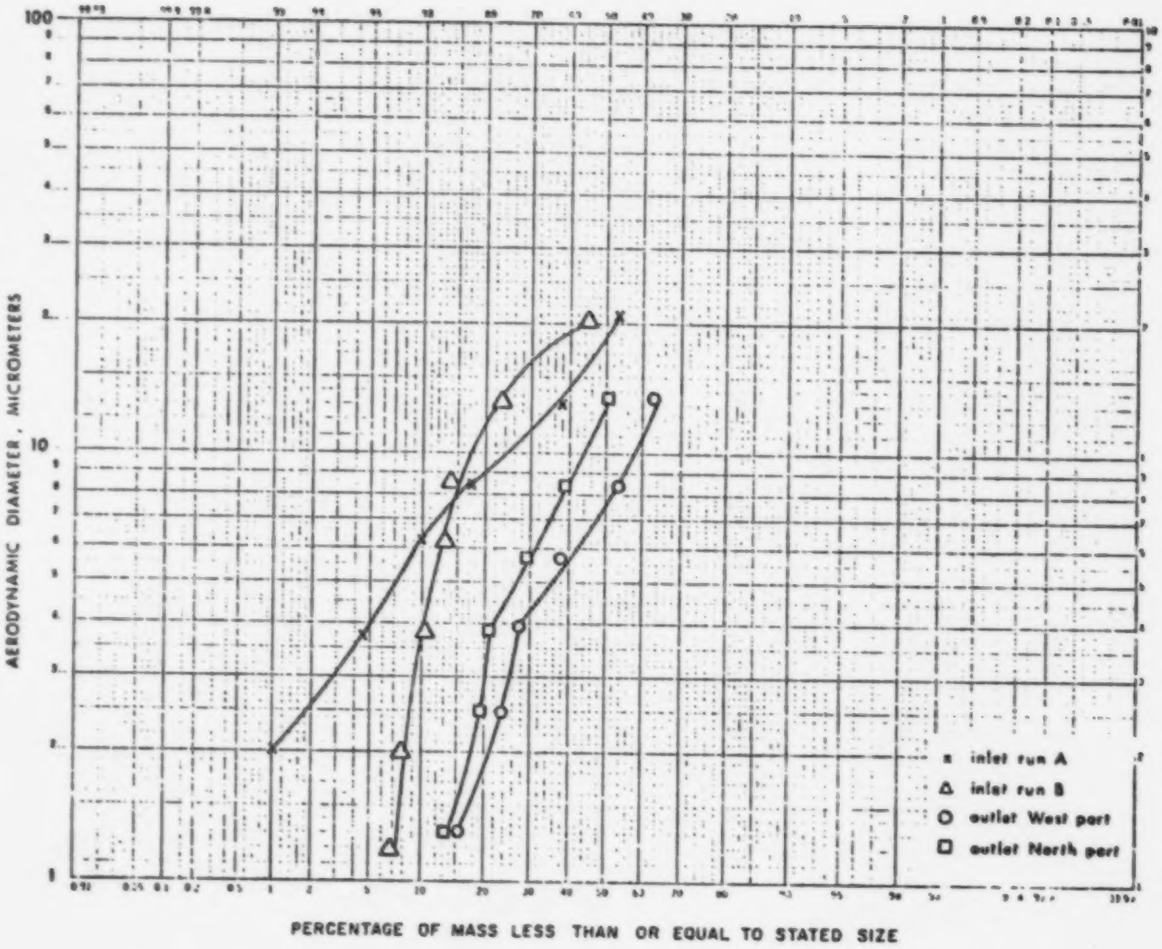

Figure 23. Cumulative particle size distributions determined by Andersen Impactors for Run 5

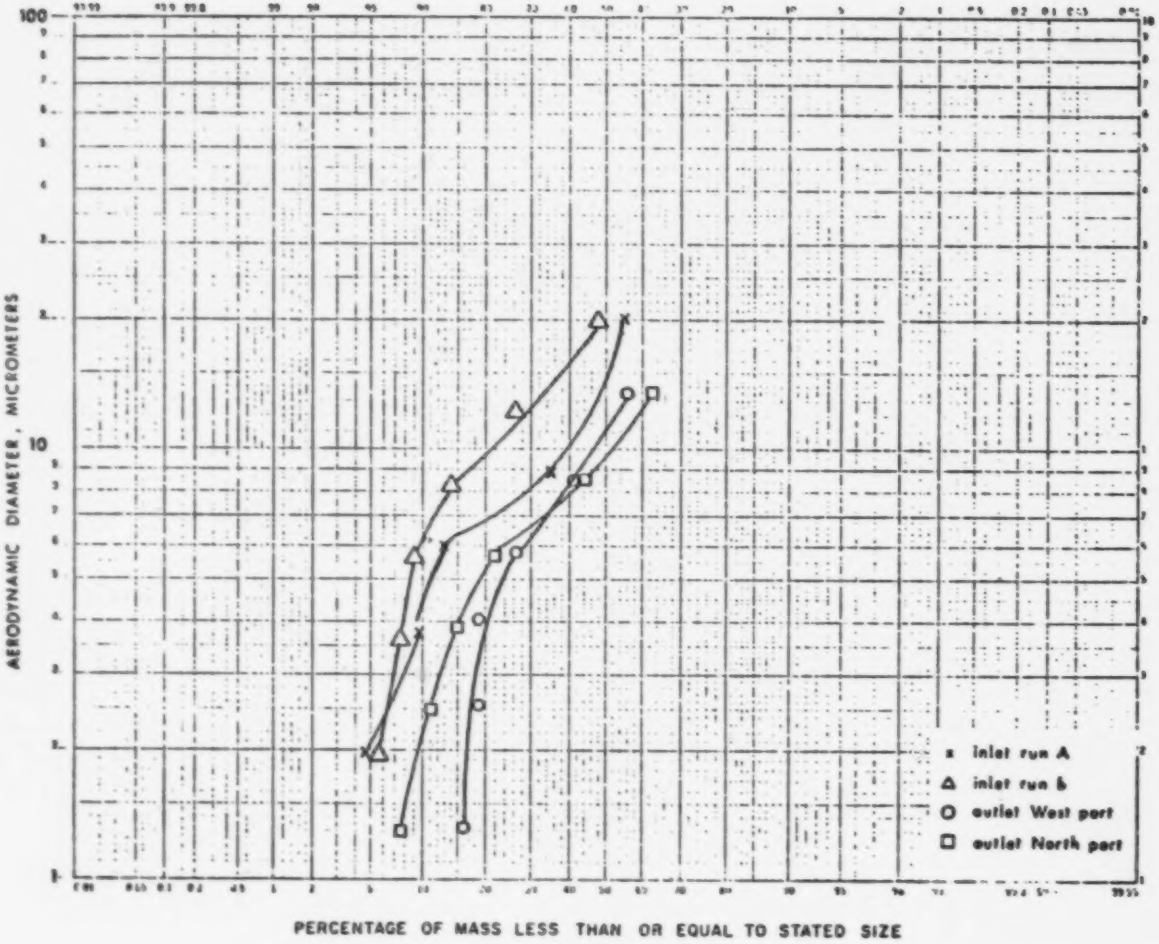

Figure 24. Cumulative particle size distributions determined by Andersen Impactors for Run 6

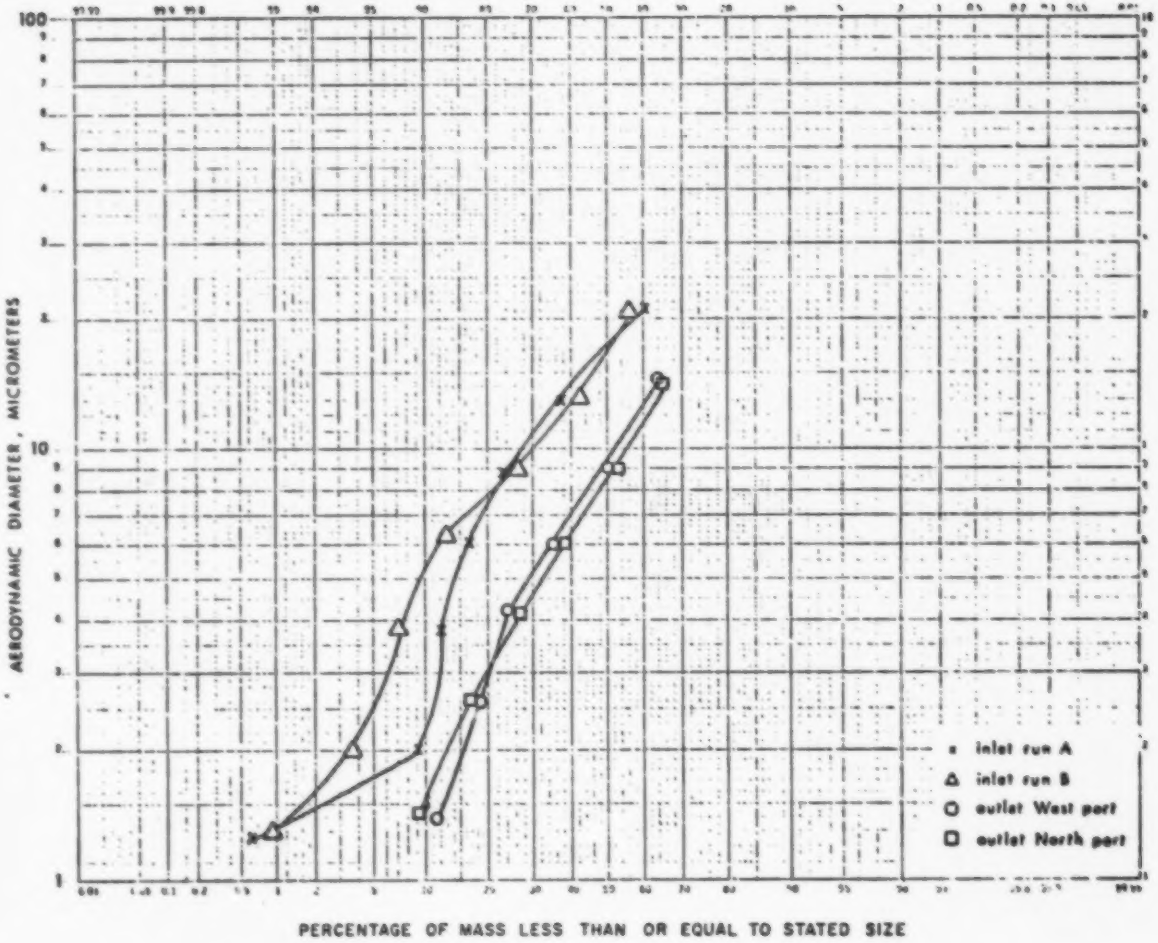

Figure 25. Cumulative particle size distributions determined by Andersen Impactors for Run 7

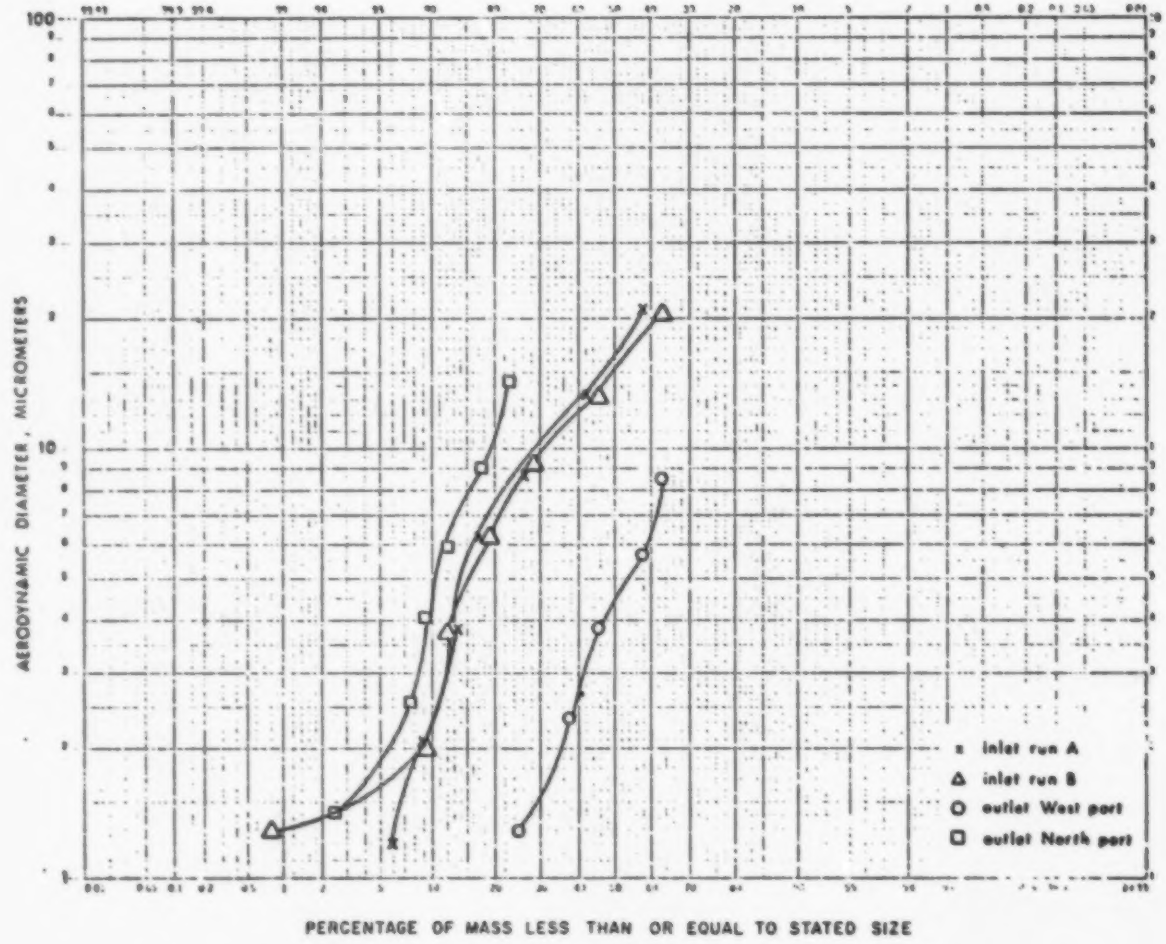

Figure 26. Cumulative particle size distributions determined by Andersen Impactors for Run 8

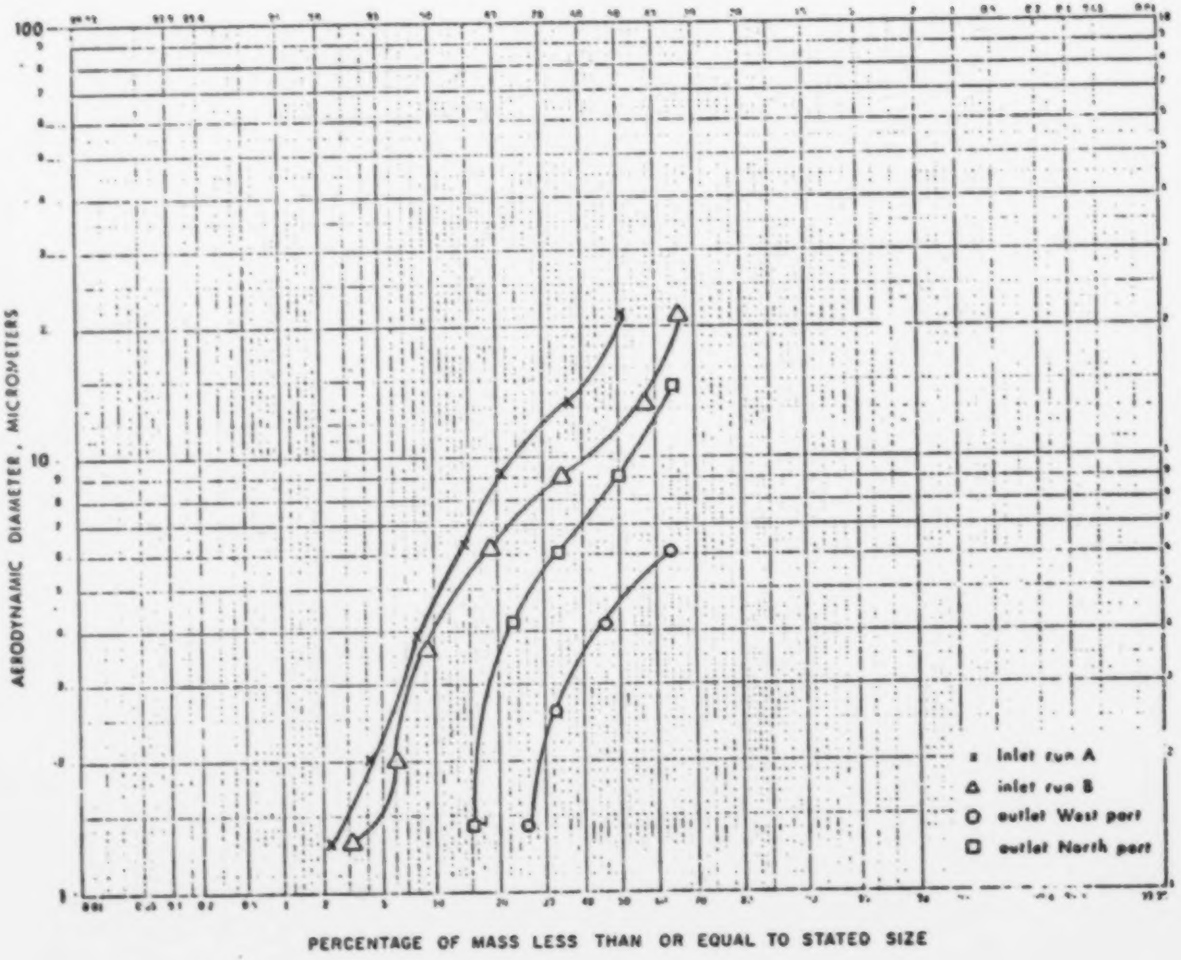

Figure 27. Cumulative particle size distributions determined by Andersen Impactors for Run 9

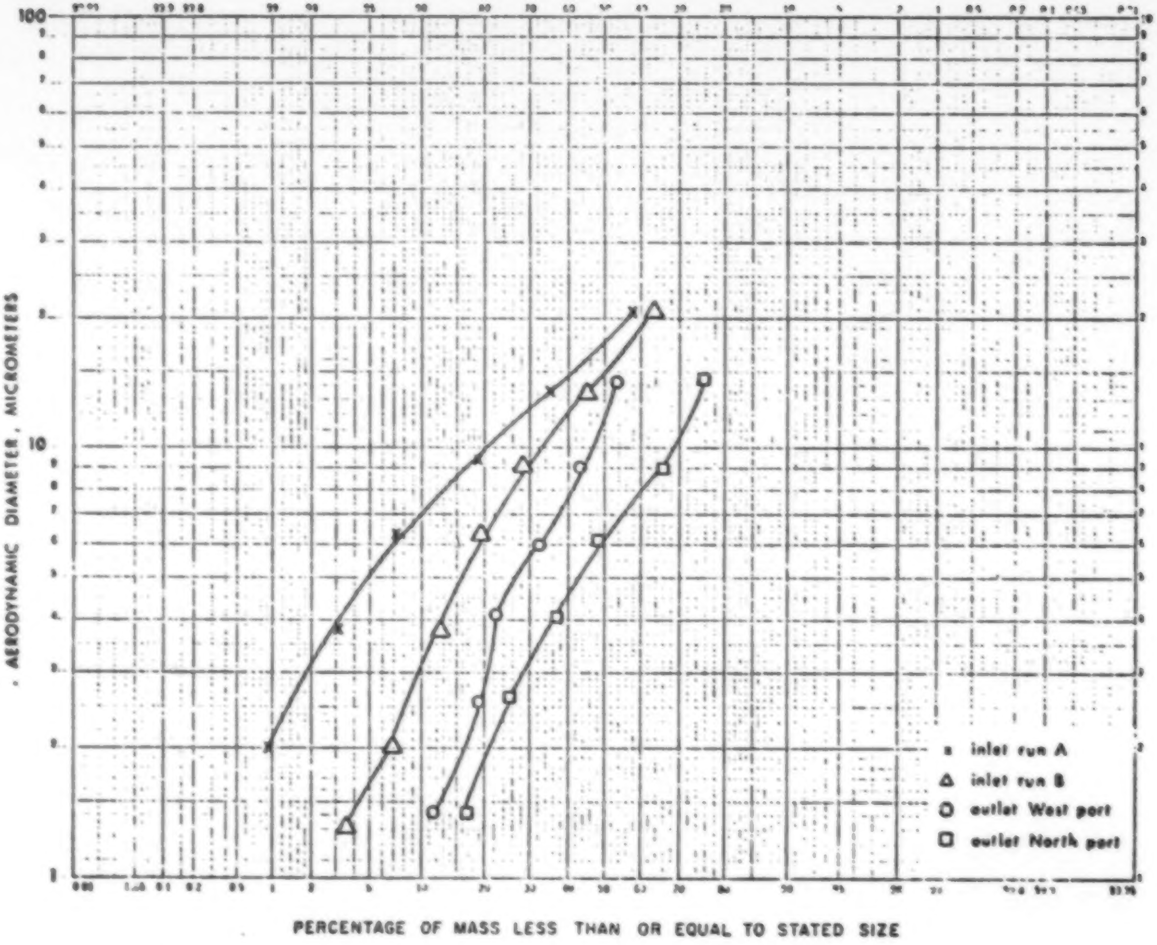

Figure 28. Cumulative particle size distributions determined by Andersen Impactors for Run 10

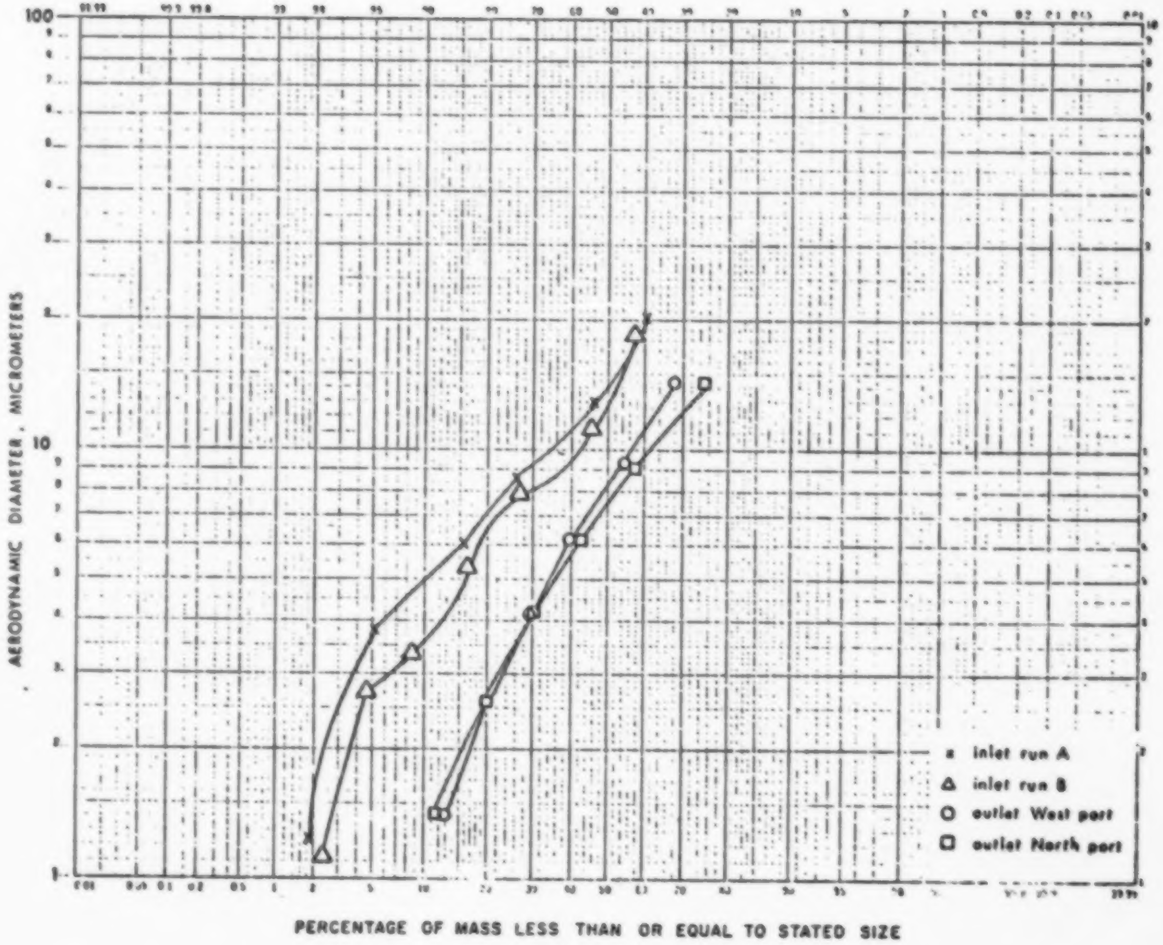

Figure 29. Cumulative particle size distributions determined by Andersen Impactors for Run 11

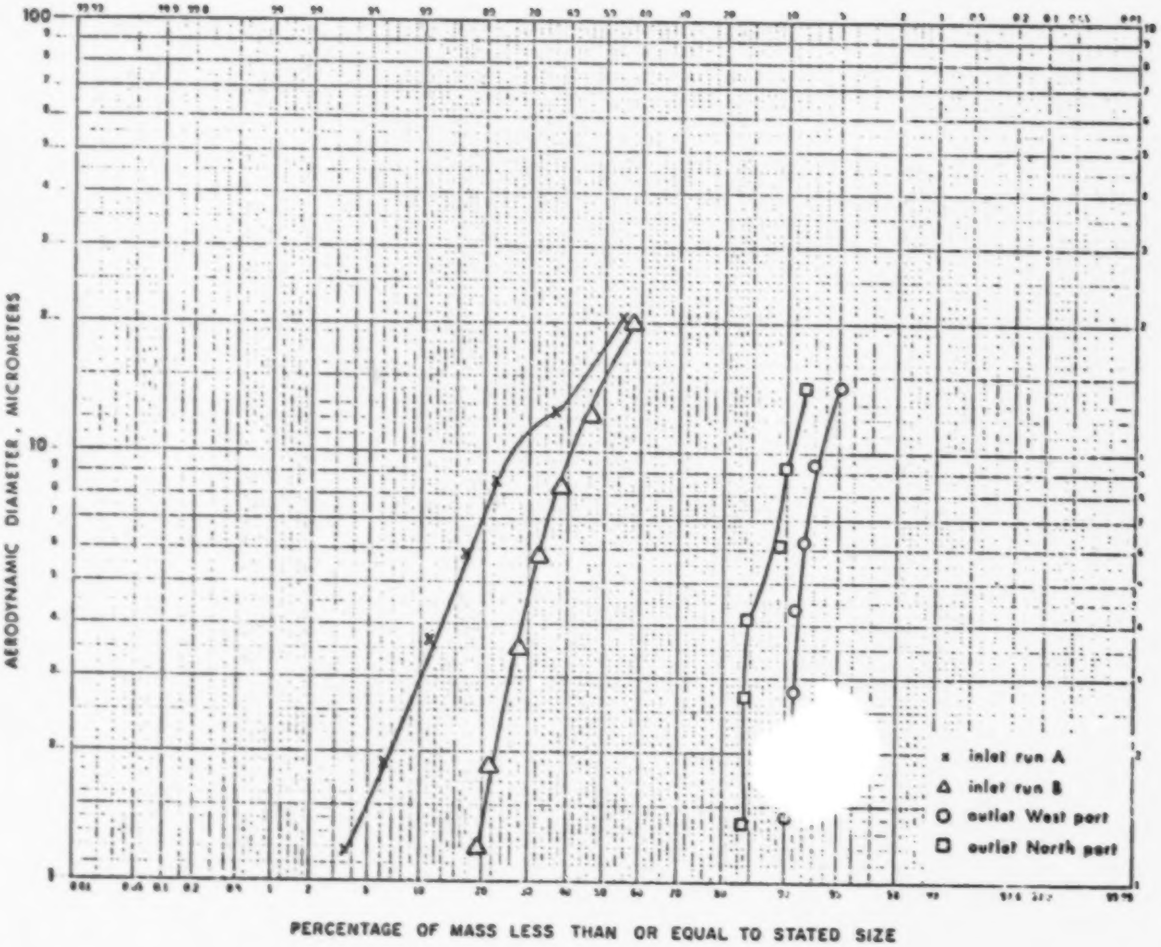

Figure 30. Cumulative particle size distributions determined by Andersen Impactors for Run 12

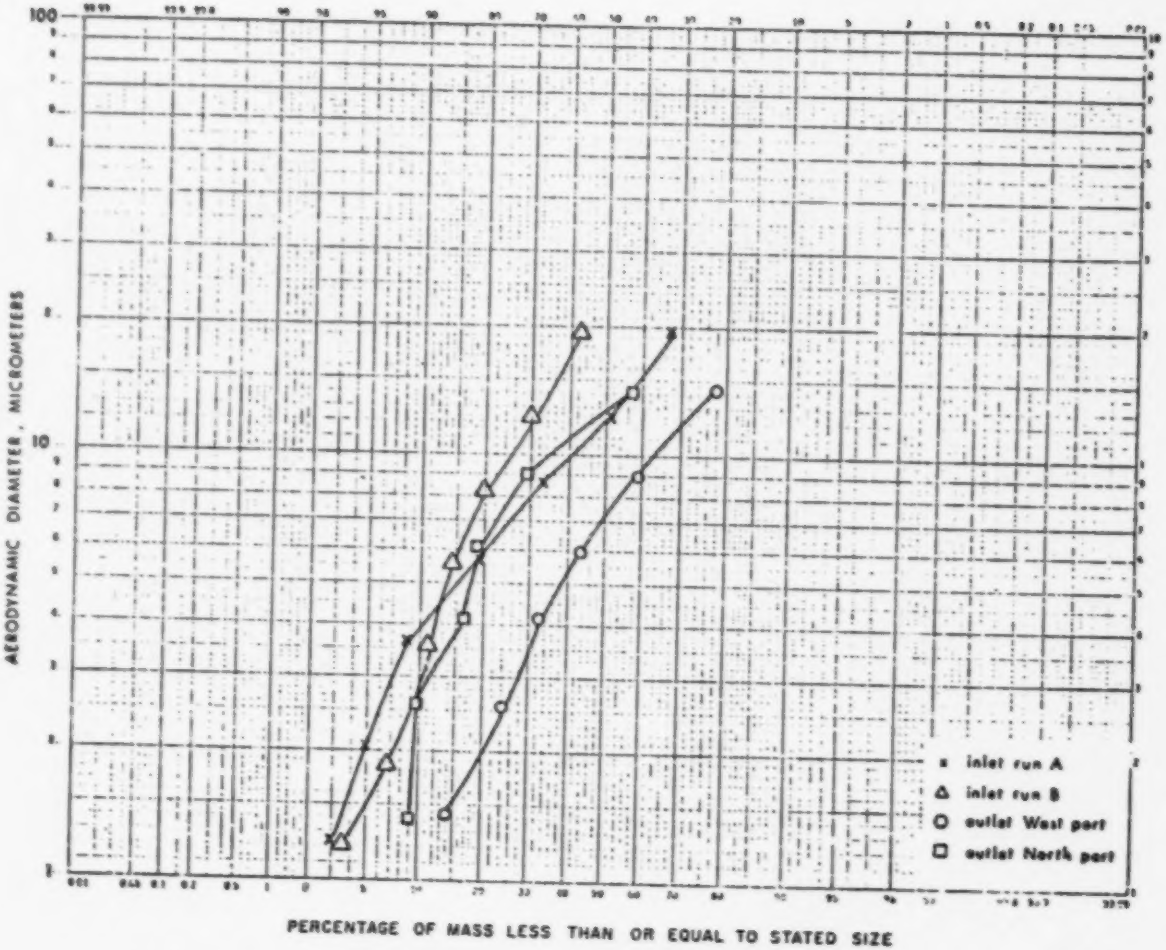

Figure 31. Cumulative particle size distributions determined by Andersen Impactors for Run 13

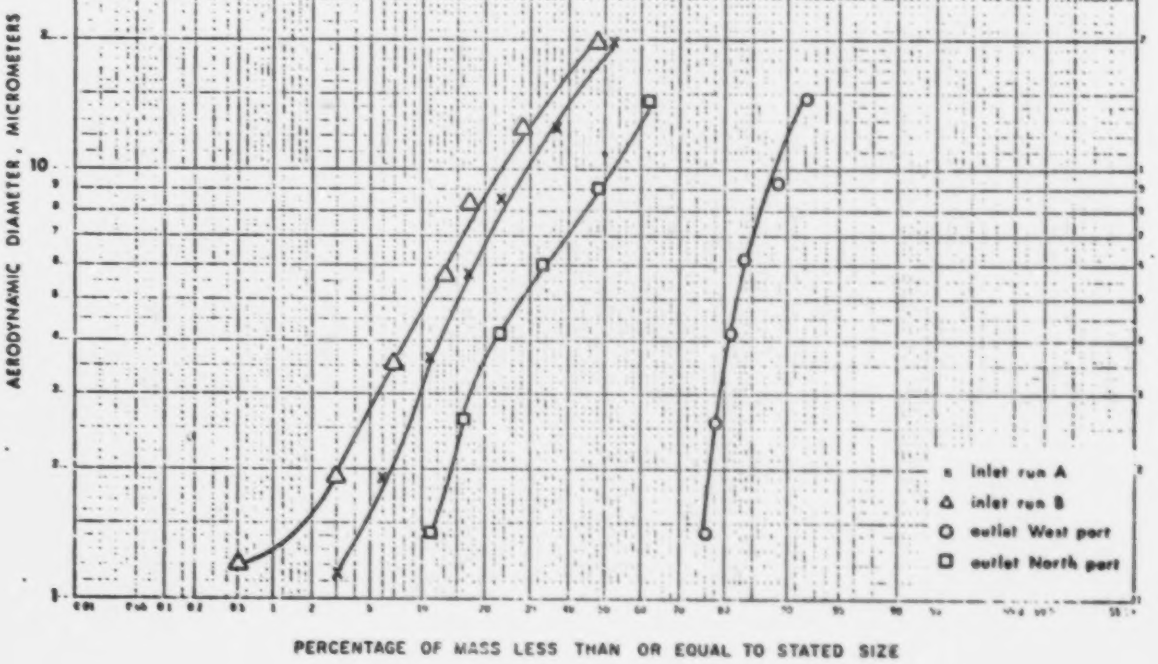

Figure 32. Cumulative particle size distributions determined by Andersen Impactors for Run 14

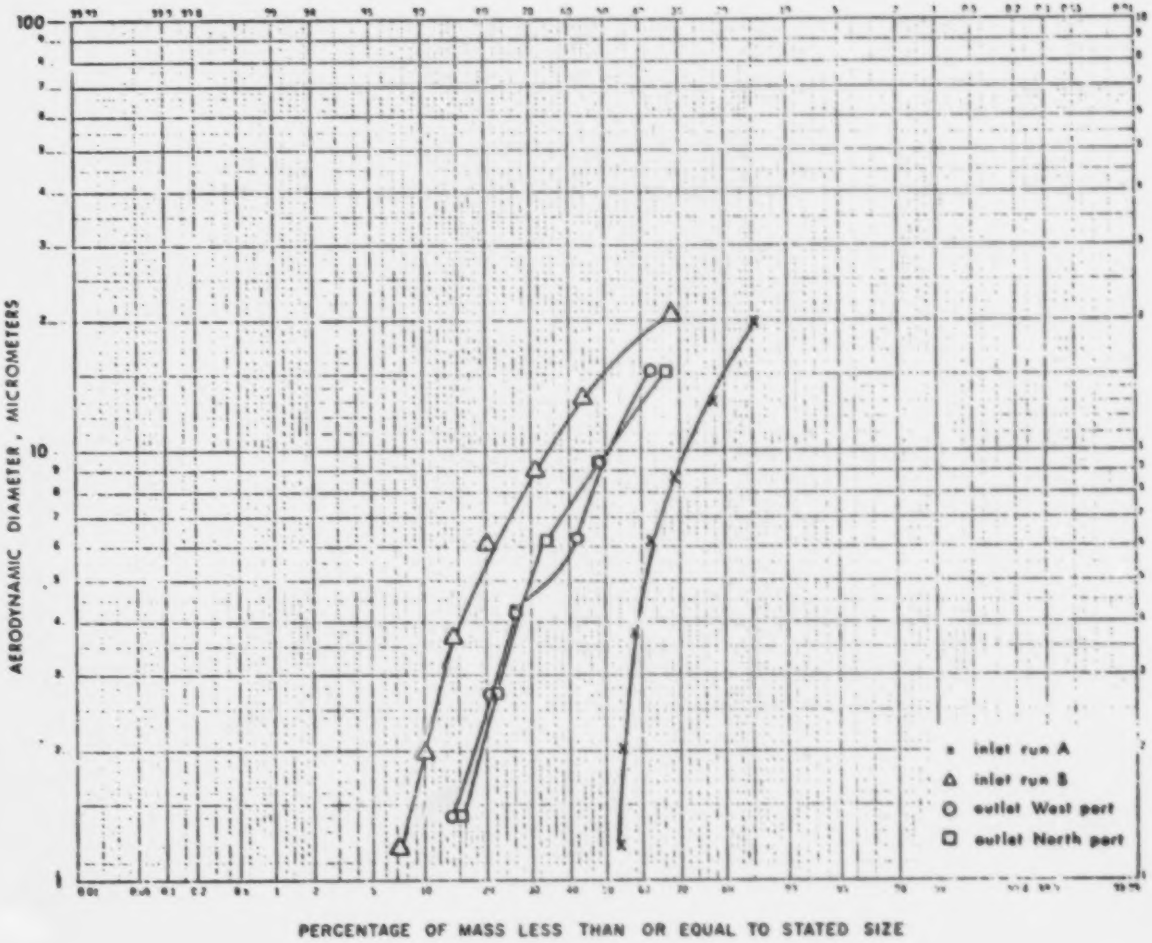

Figure 33. Cumulative particle size distributions determined by Andersen Impactors for Run 15

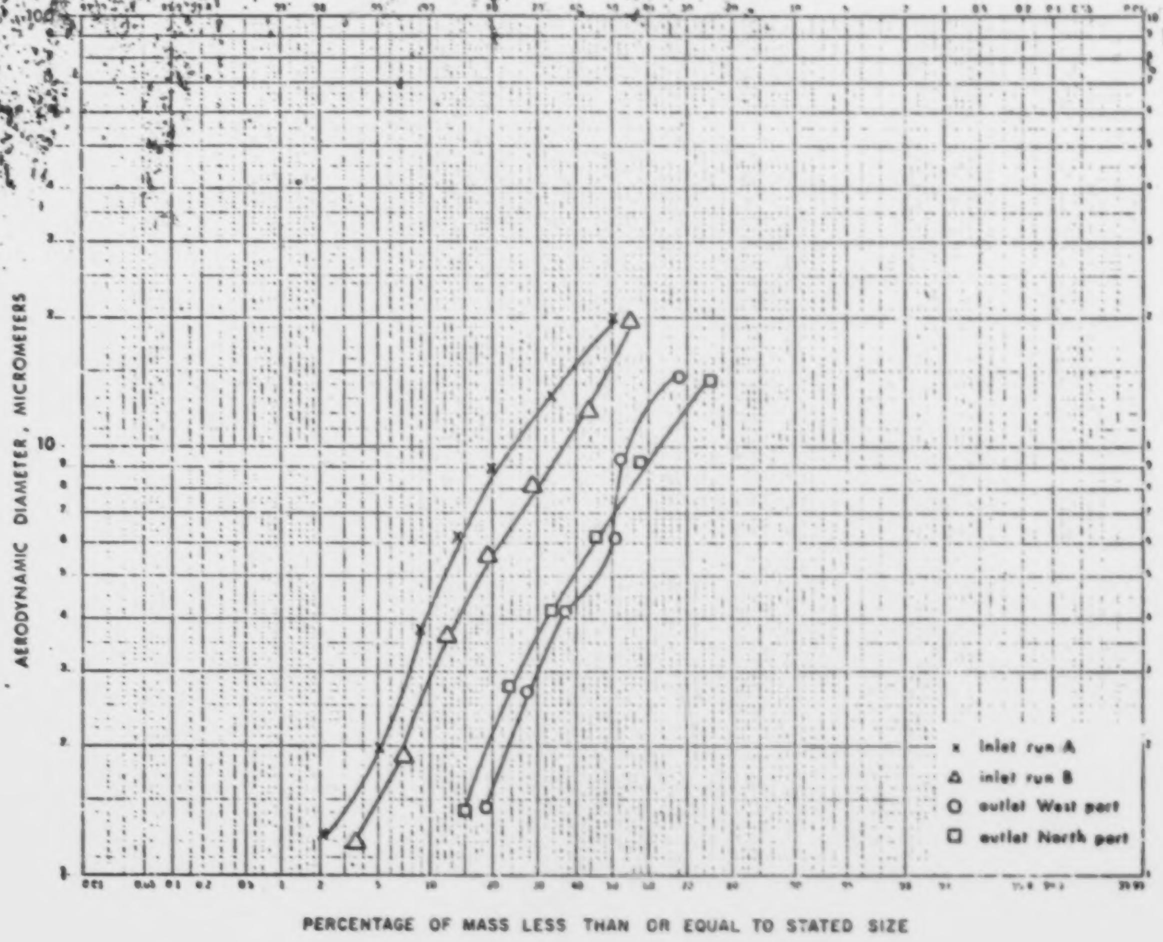

Figure 34. Cumulative particle size distributions determined by Andersen Impactors for Run 16

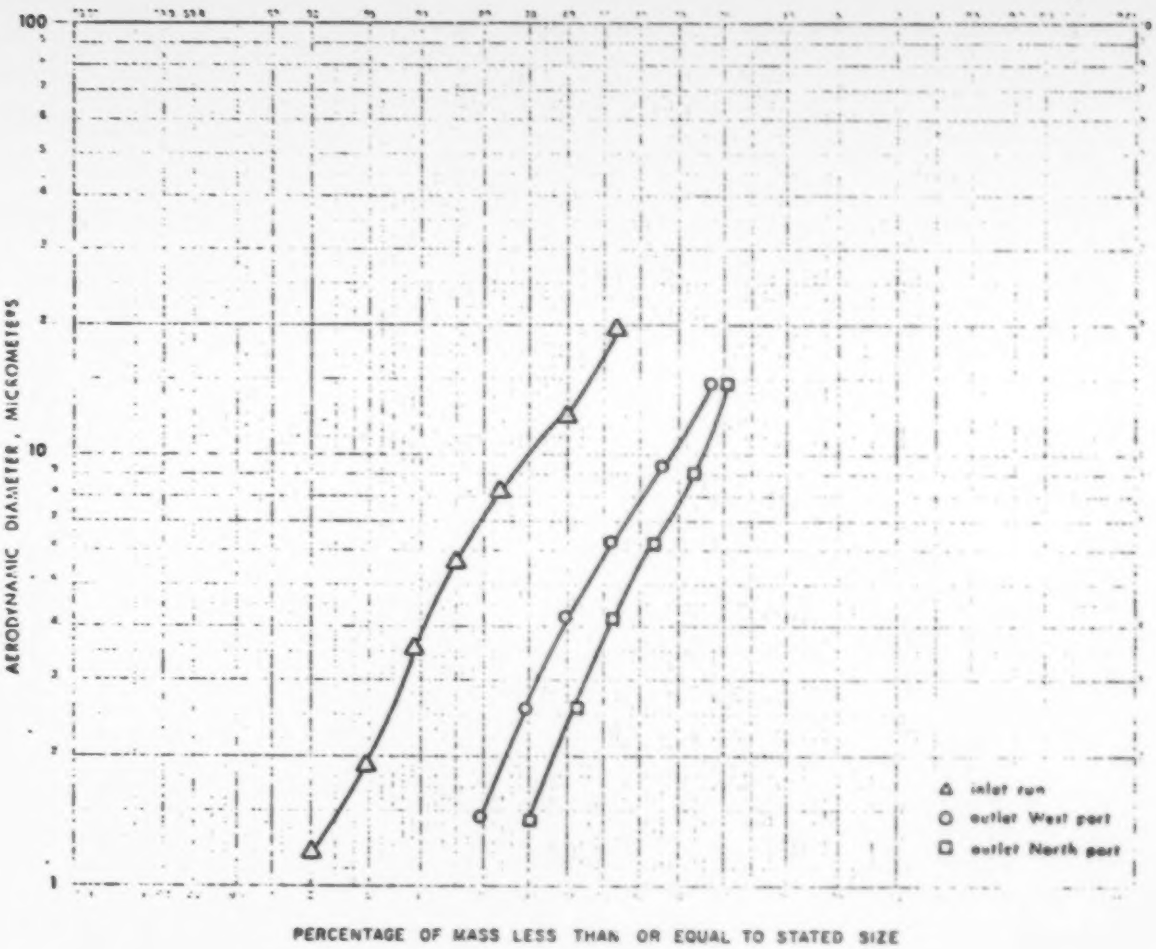

Figure 35. Cumulative particle size distributions determined by Andersen Impactors for Run 17

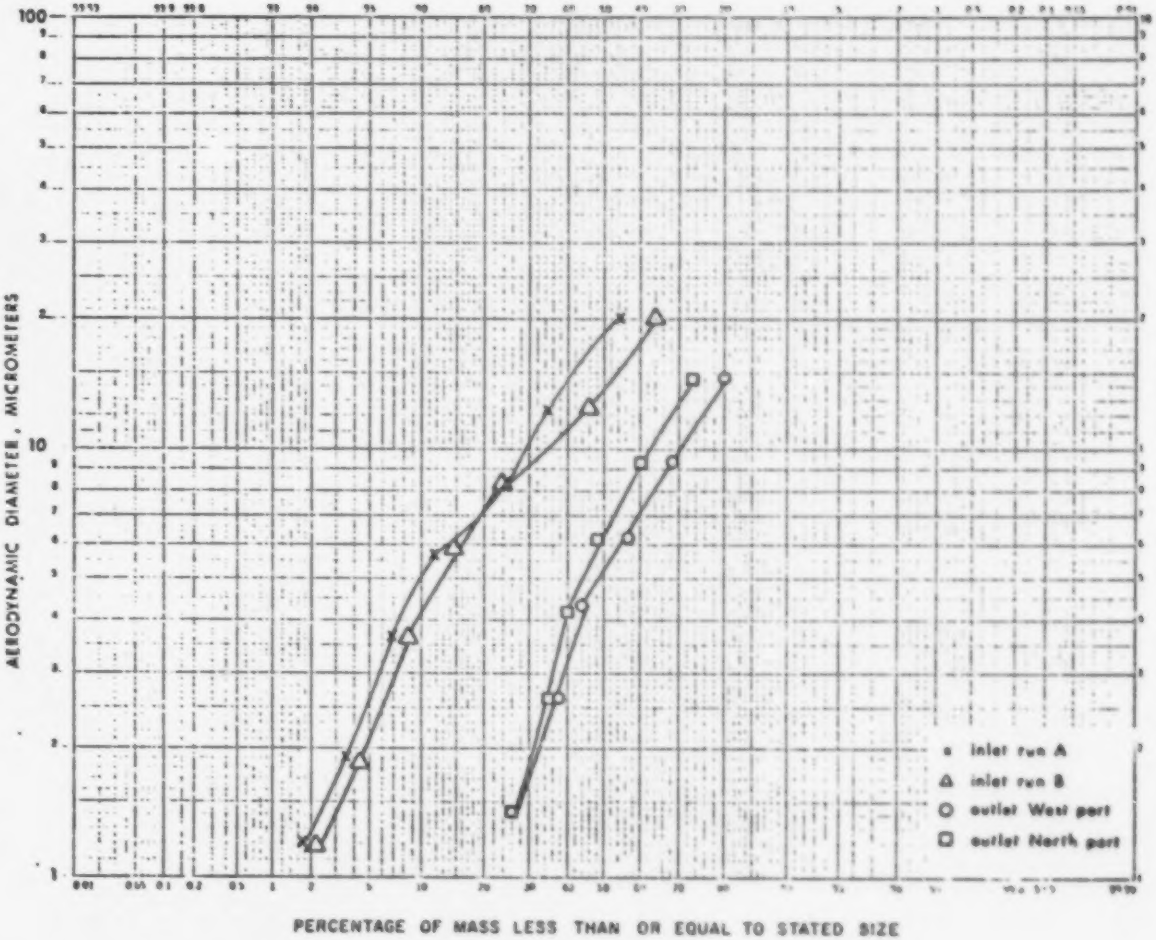

Figure 36. Cumulative particle size distributions determined by Andersen Impactors for Run 18

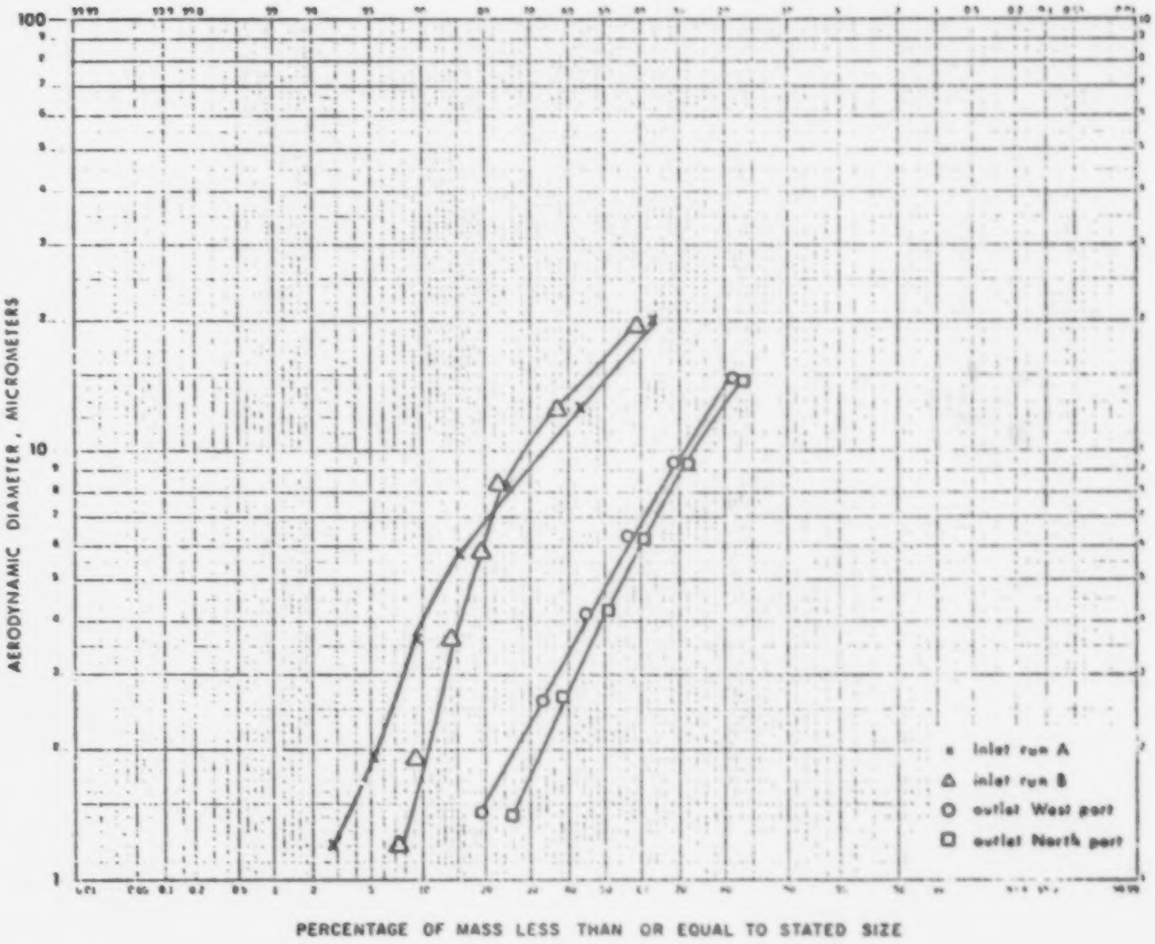

Figure 37. Cumulative particle size distributions determined by Andersen Impactors for Run 19

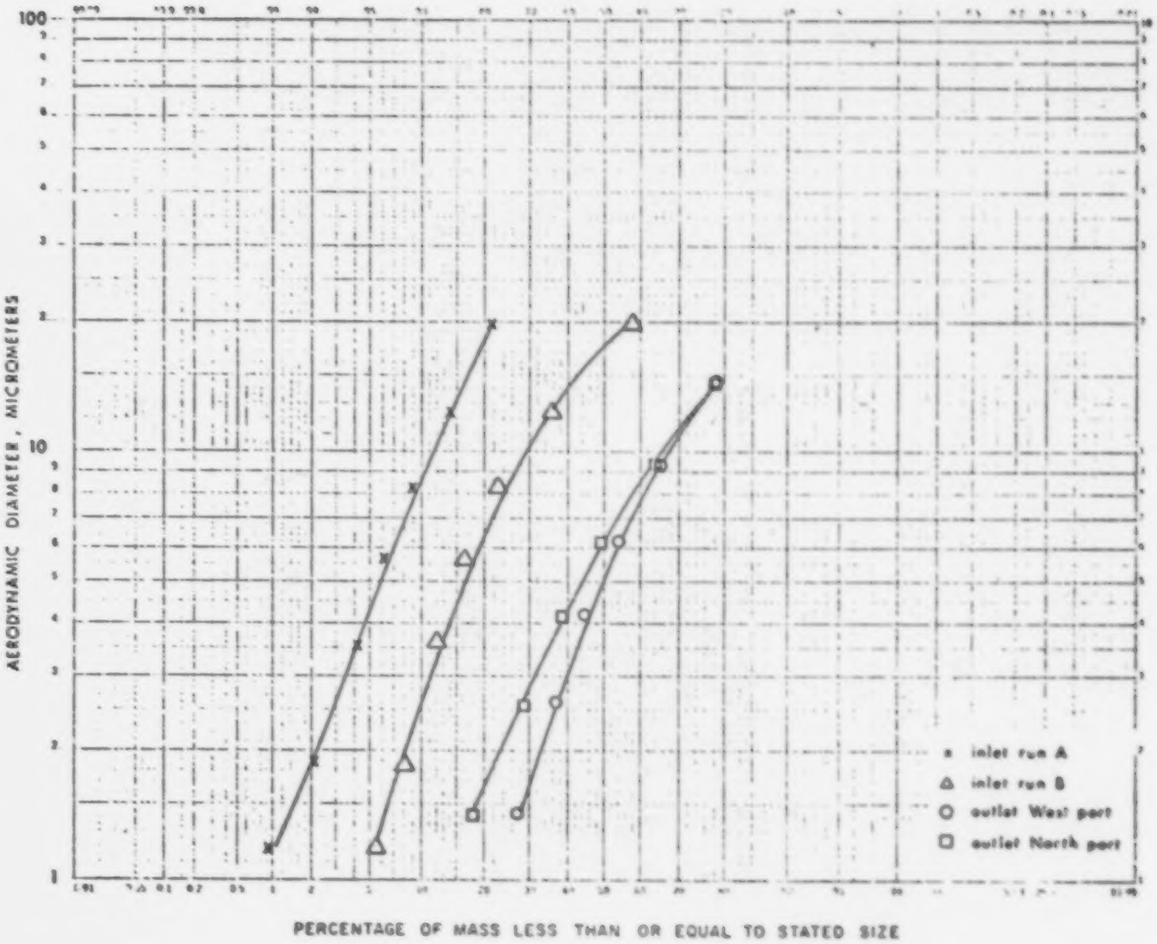

Figure 38. Cumulative particle size distributions determined by Andersen Impactors for Run 20

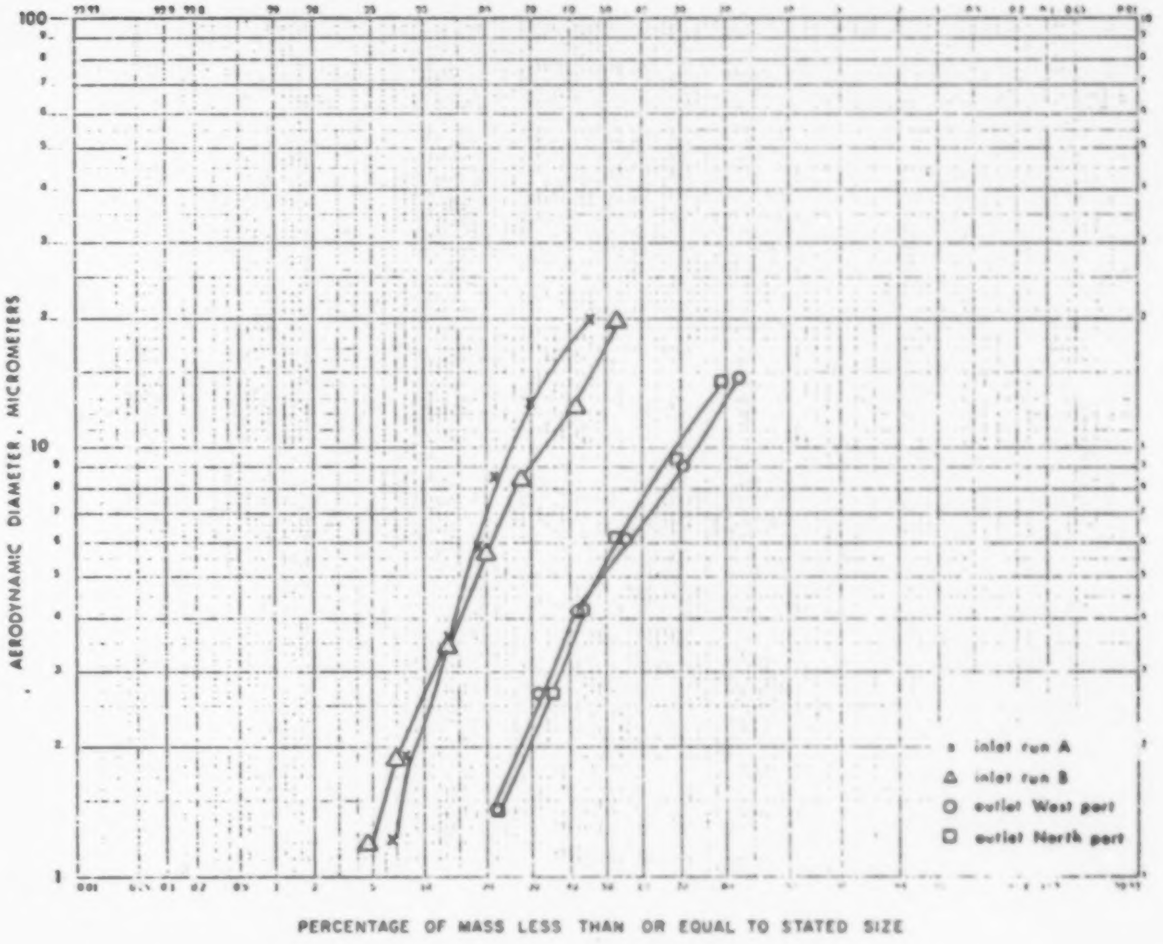

Figure 39. Cumulative particle size distributions determined by Andersen Impactors for Run 21

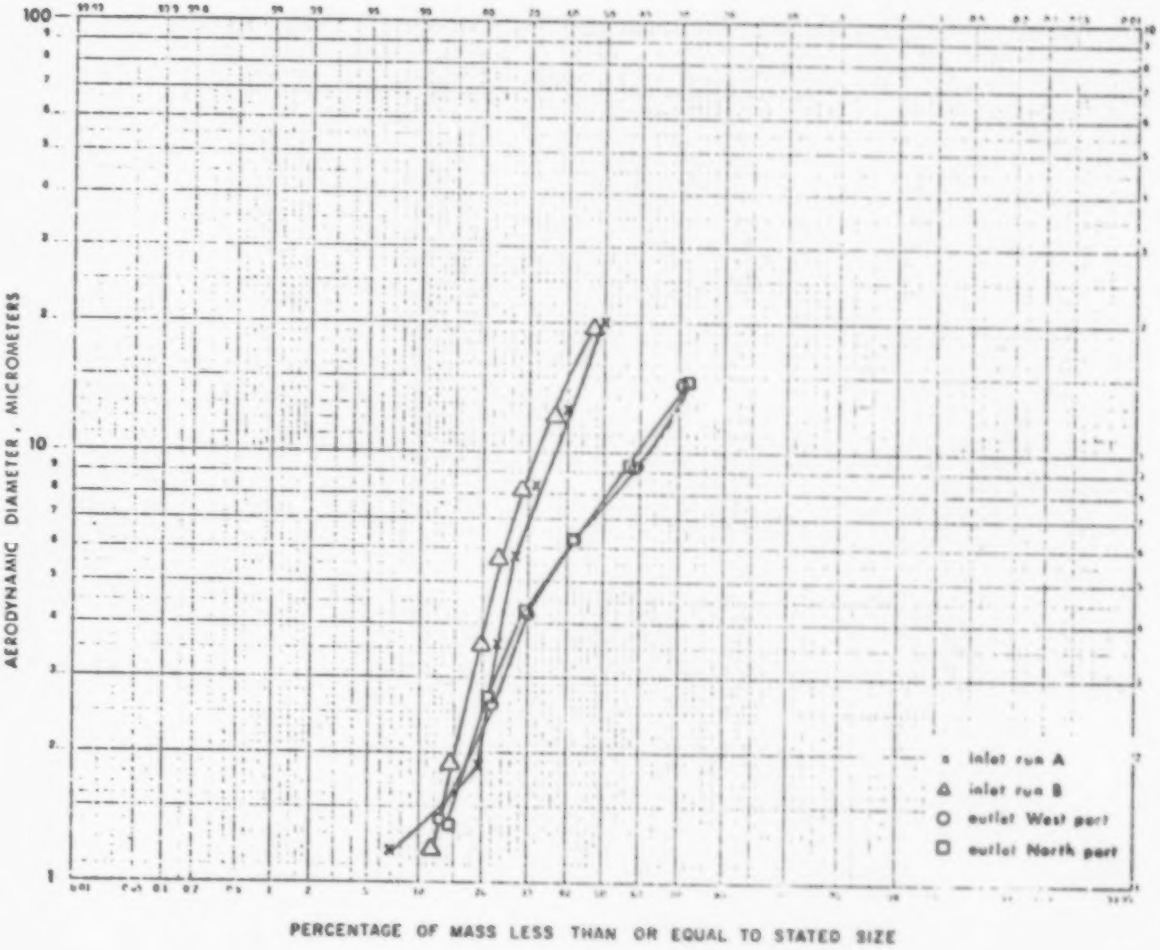

Figure 40. Cumulative particle size distributions determined by Andersen Impactors for Run 22

APPENDIX B

DIFFERENTIAL SIZE DISTRIBUTION CURVES

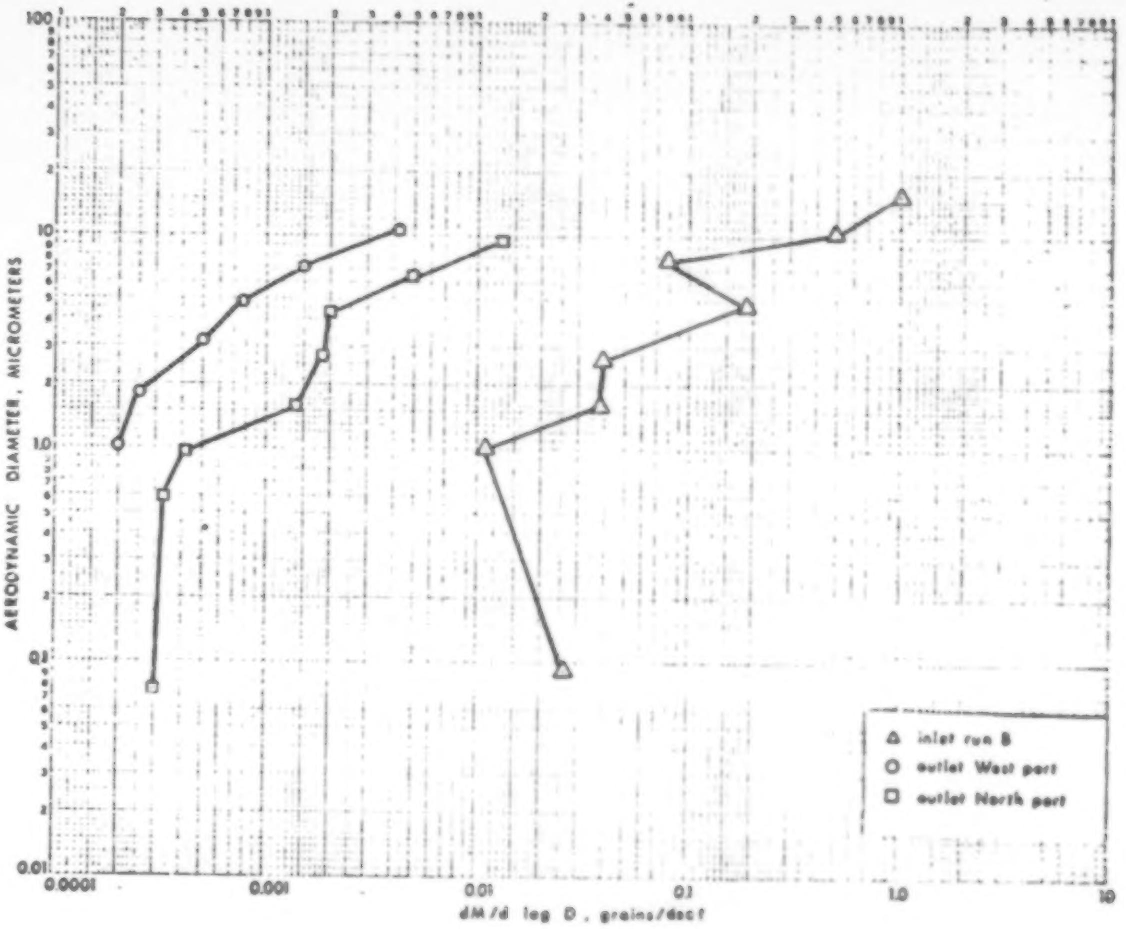

Figure 41. Differential particle size distributions determined by Andersen Impactors for Run 1

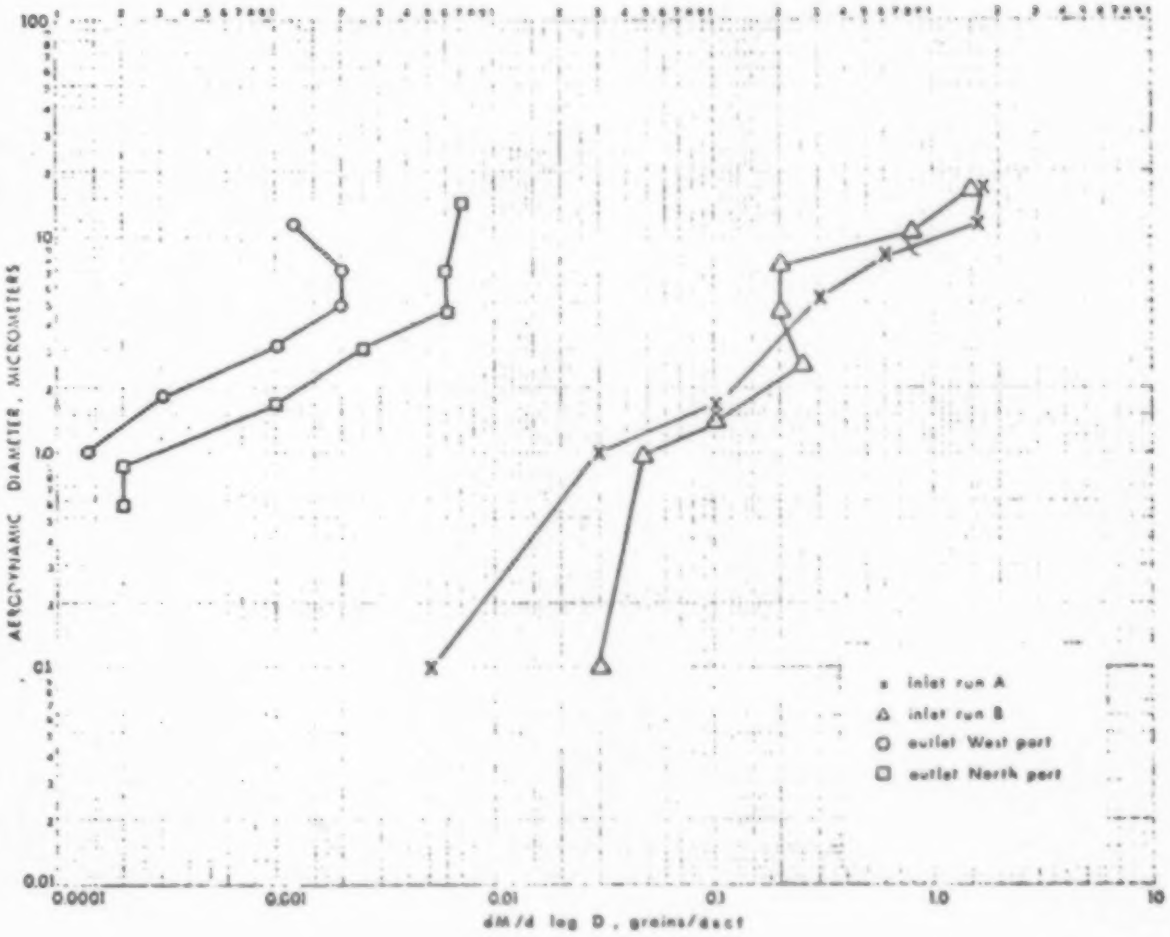

Figure 42. Differential particle size distributions determined by Andersen Impactors for Run 2

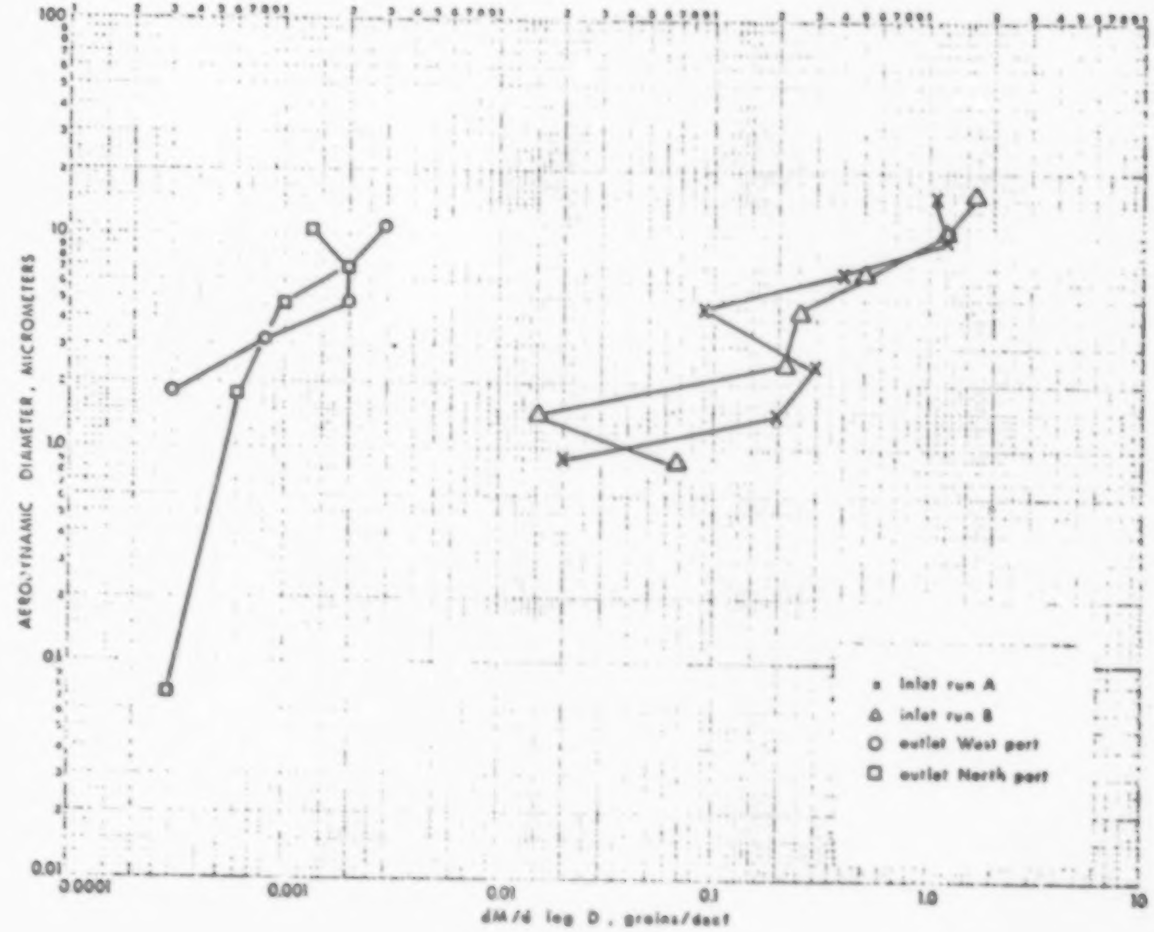

Figure 43. Differential particle size distributions determined by Andersen Impactors for Run 3

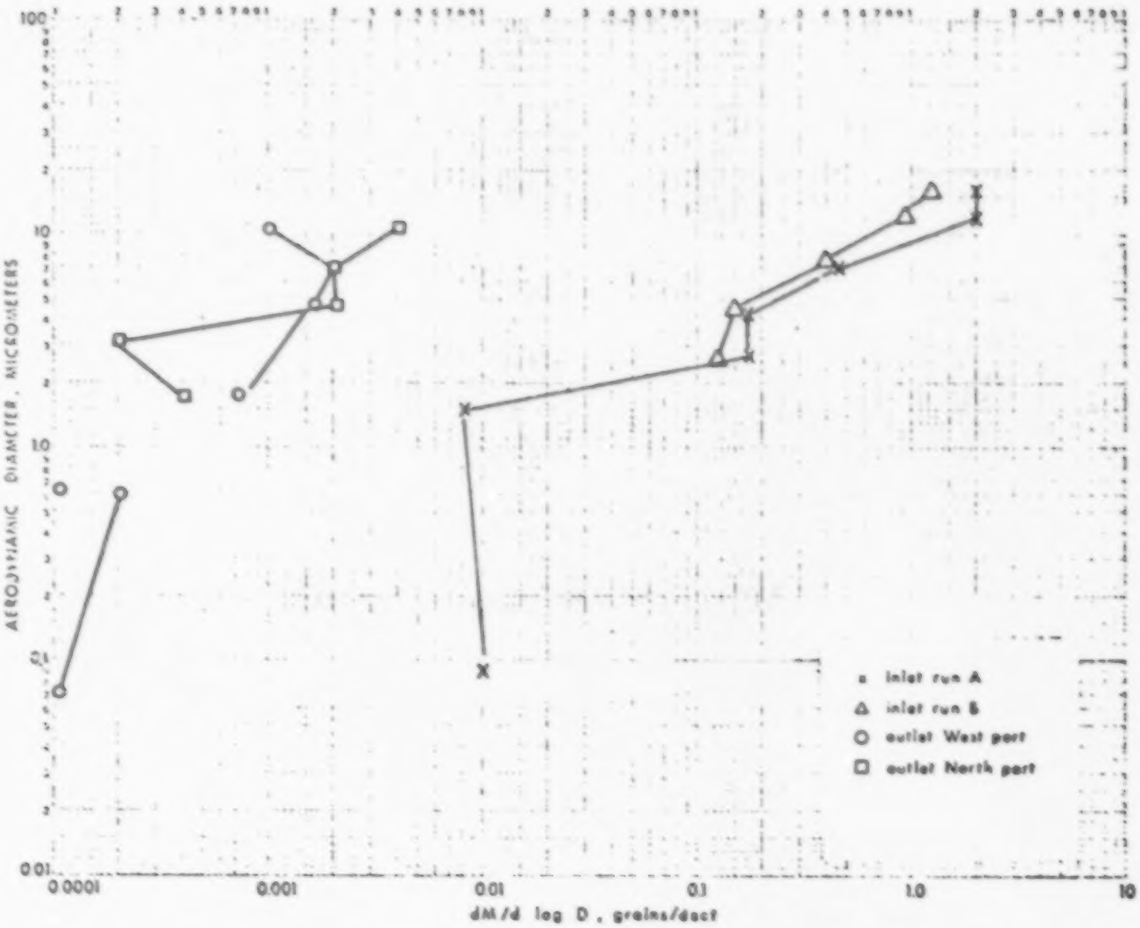

Figure 44. Differential particle size distributions determined by Andersen Impactors for Run 4

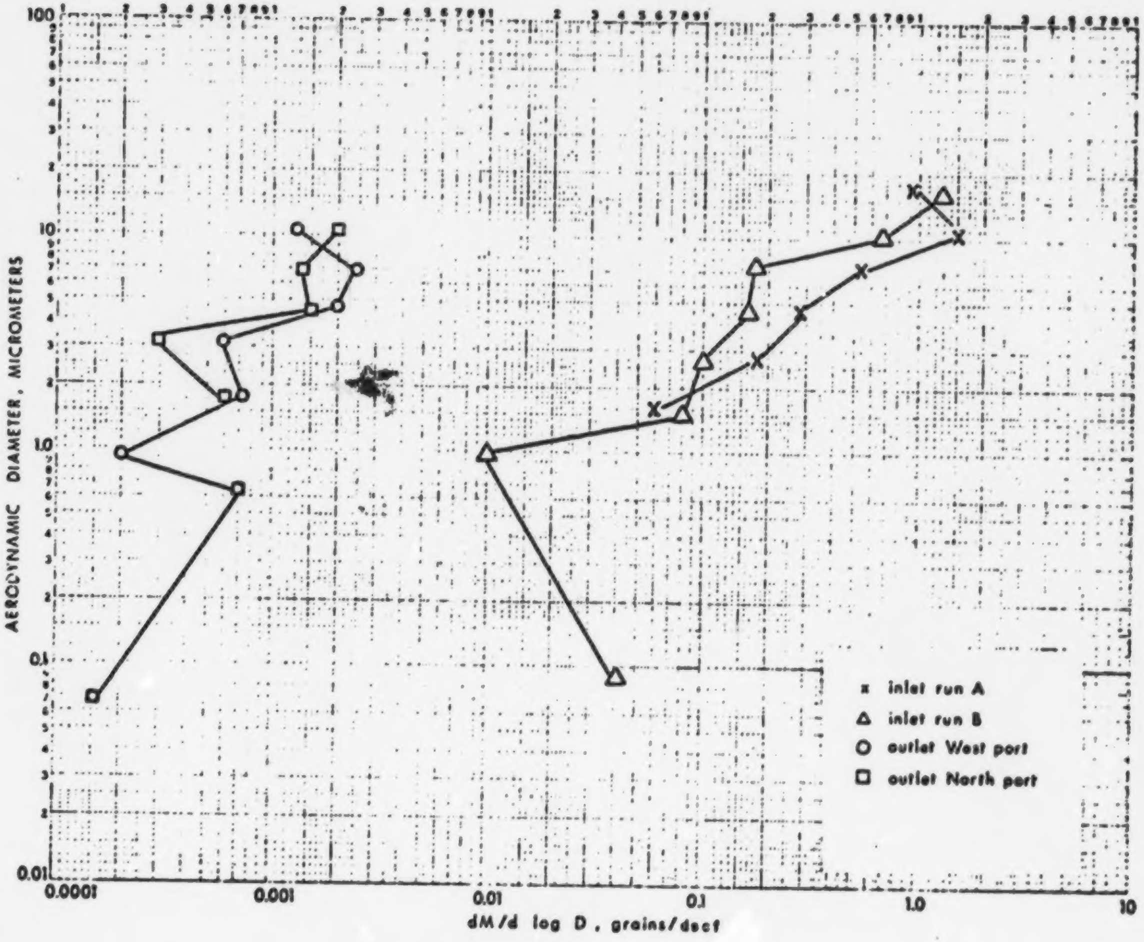

Figure 45. Differential particle size distributions determined by Andersen Impactors for Run 5

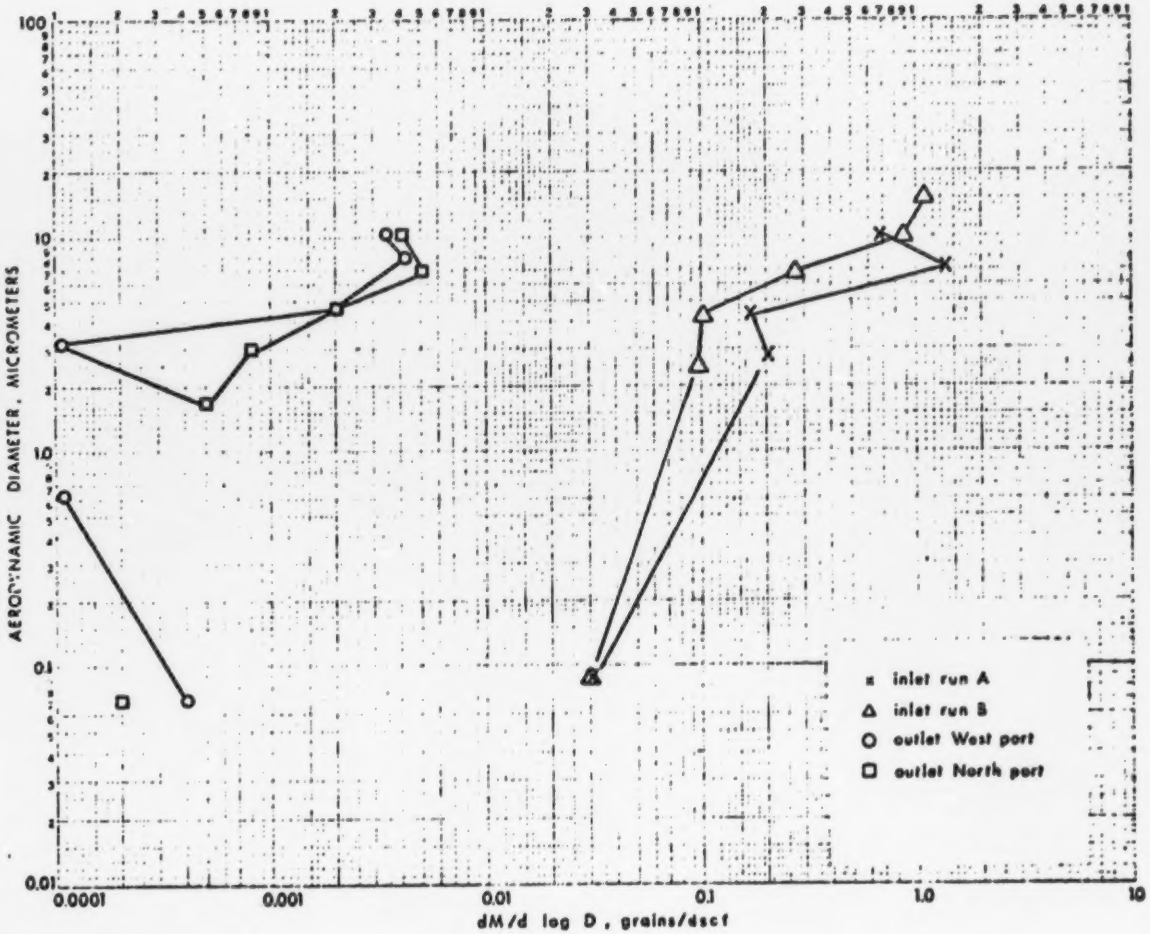

Figure 46. Differential particle size distributions determined by Andersen Impactors for Run 6

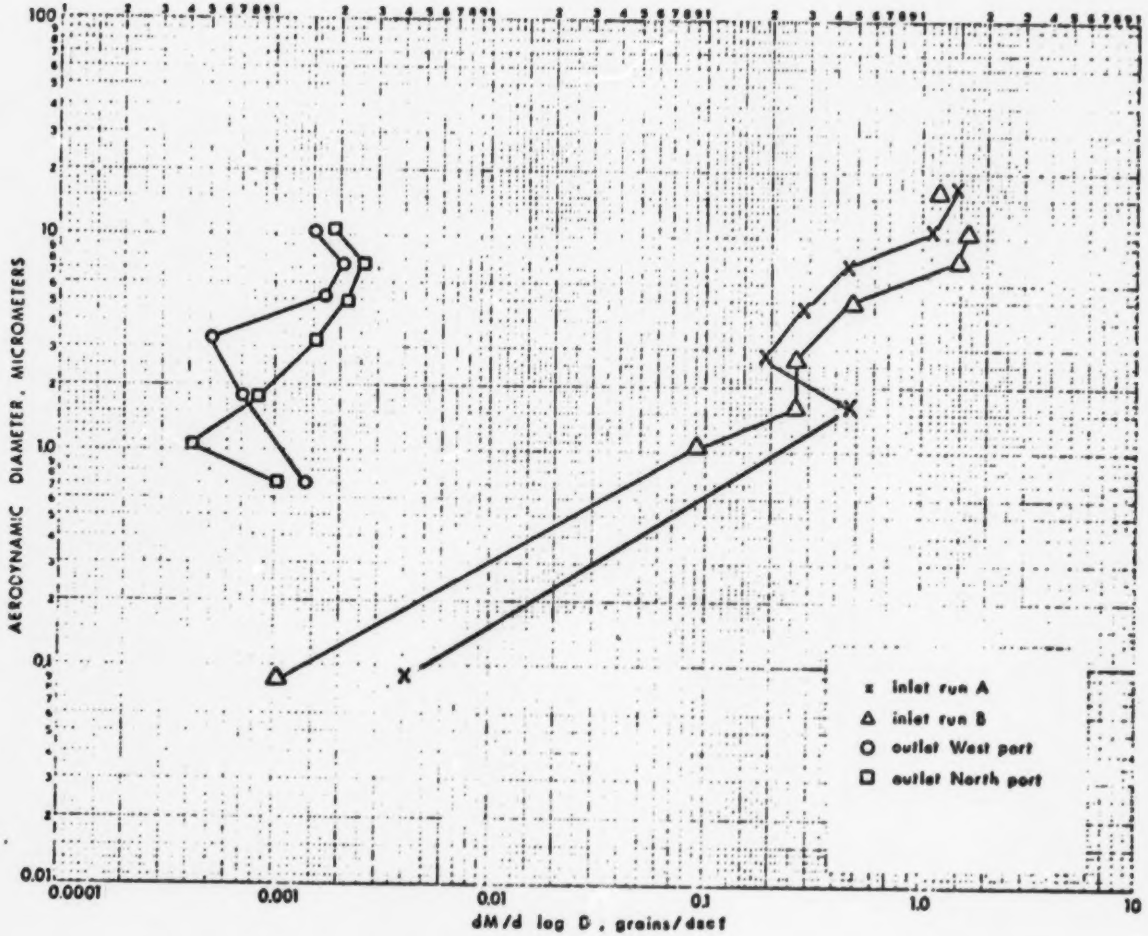

Figure 47. Differential particle size distributions determined by Andersen Impactors for Run 7

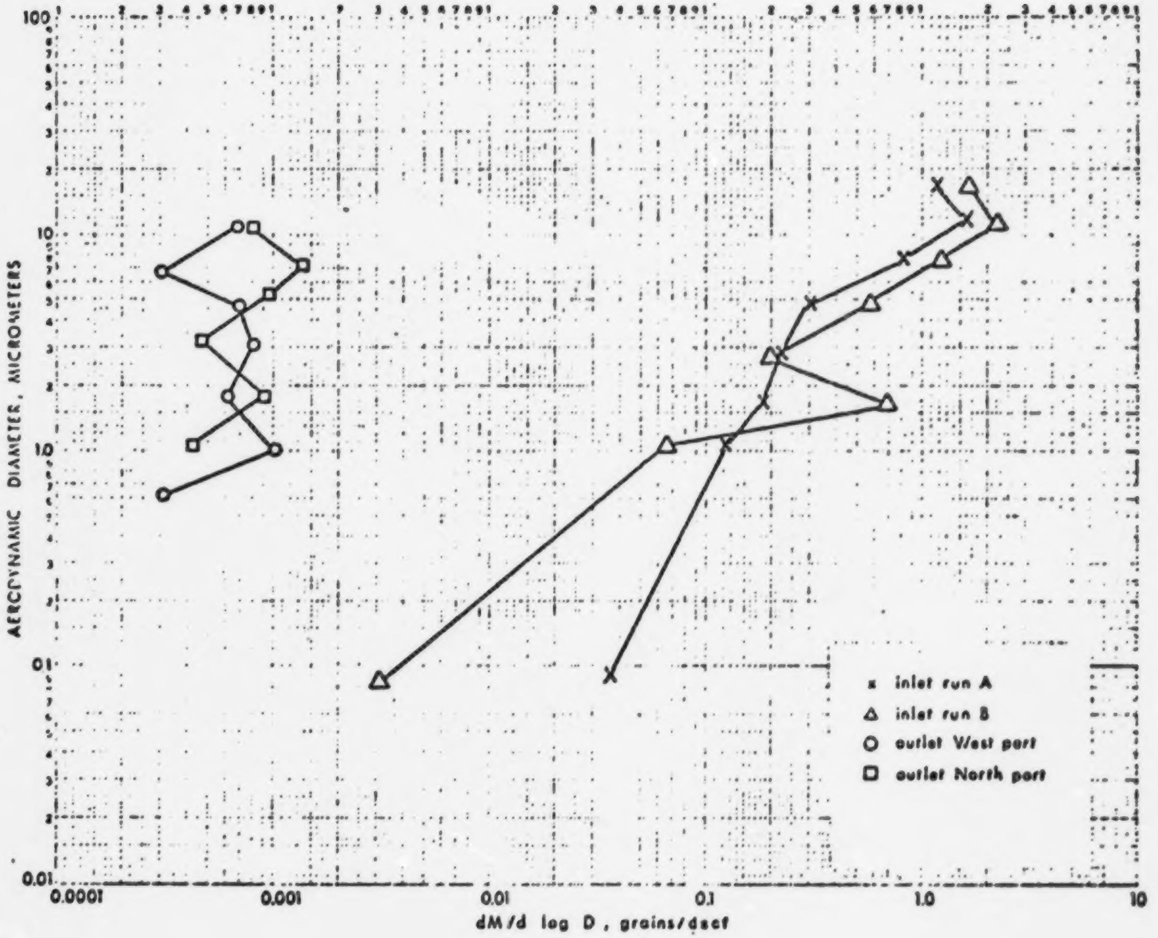

Figure 48. Differential particle size distributions determined by Andersen Impactors for Run 8

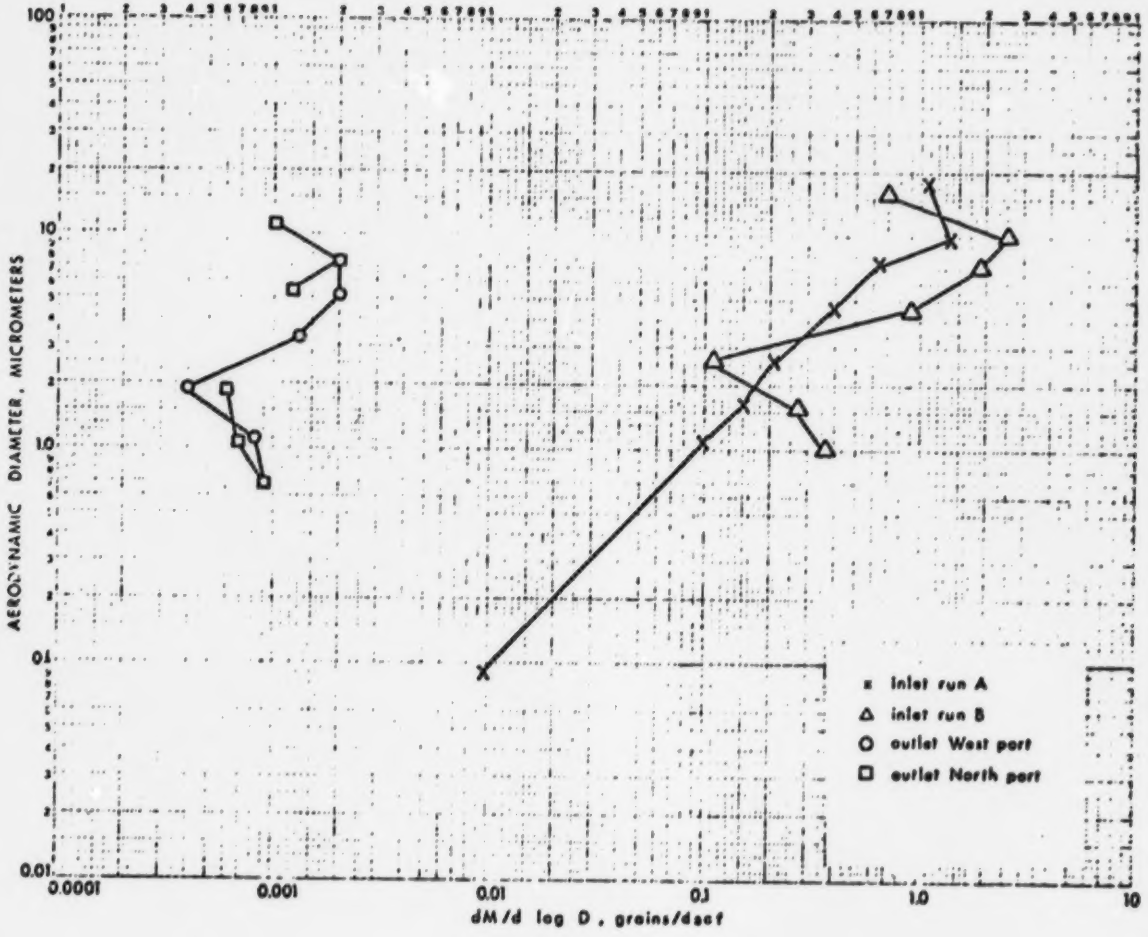

Figure 49. Differential particle size distributions determined by Andersen Impactors for Run 9

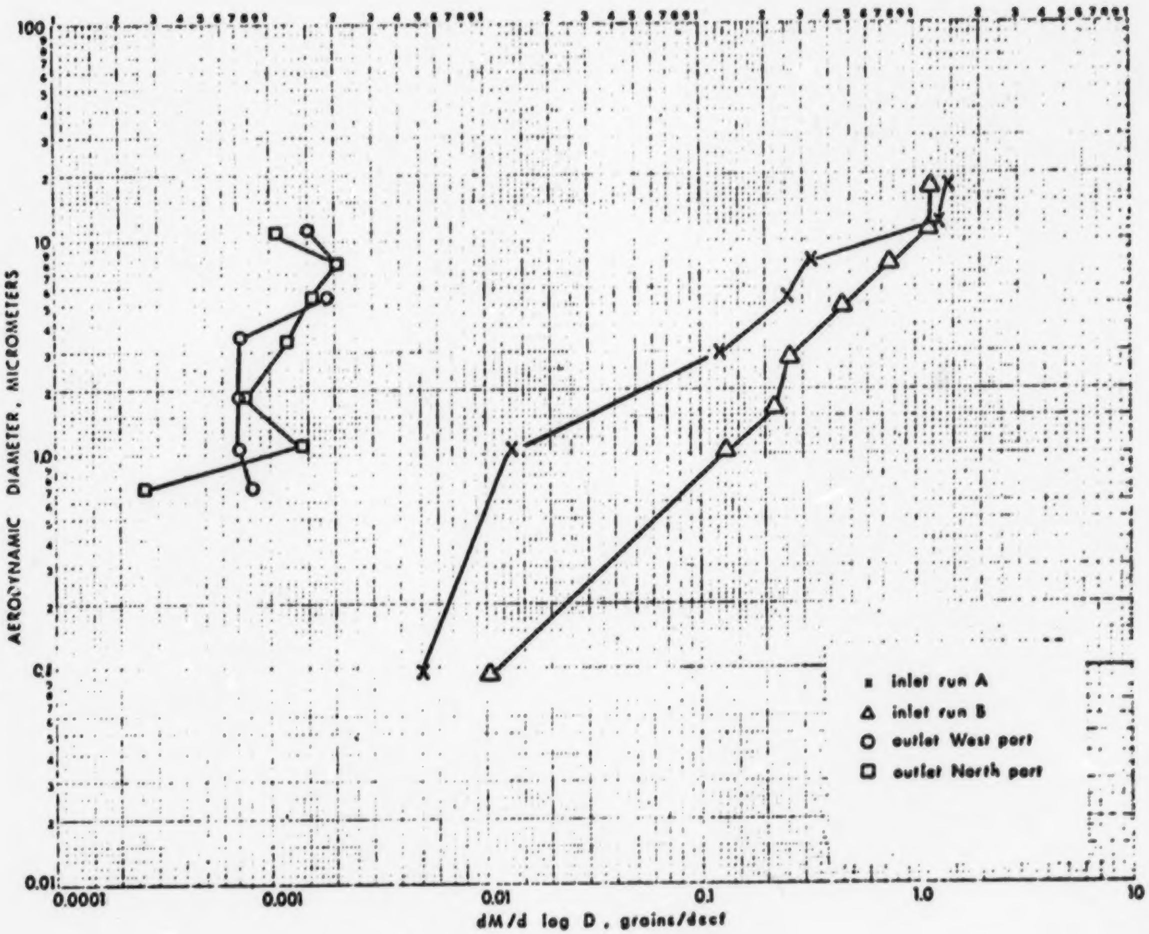

Figure 50. Differential particle size distributions determined by Andersen Impactors for Run 10

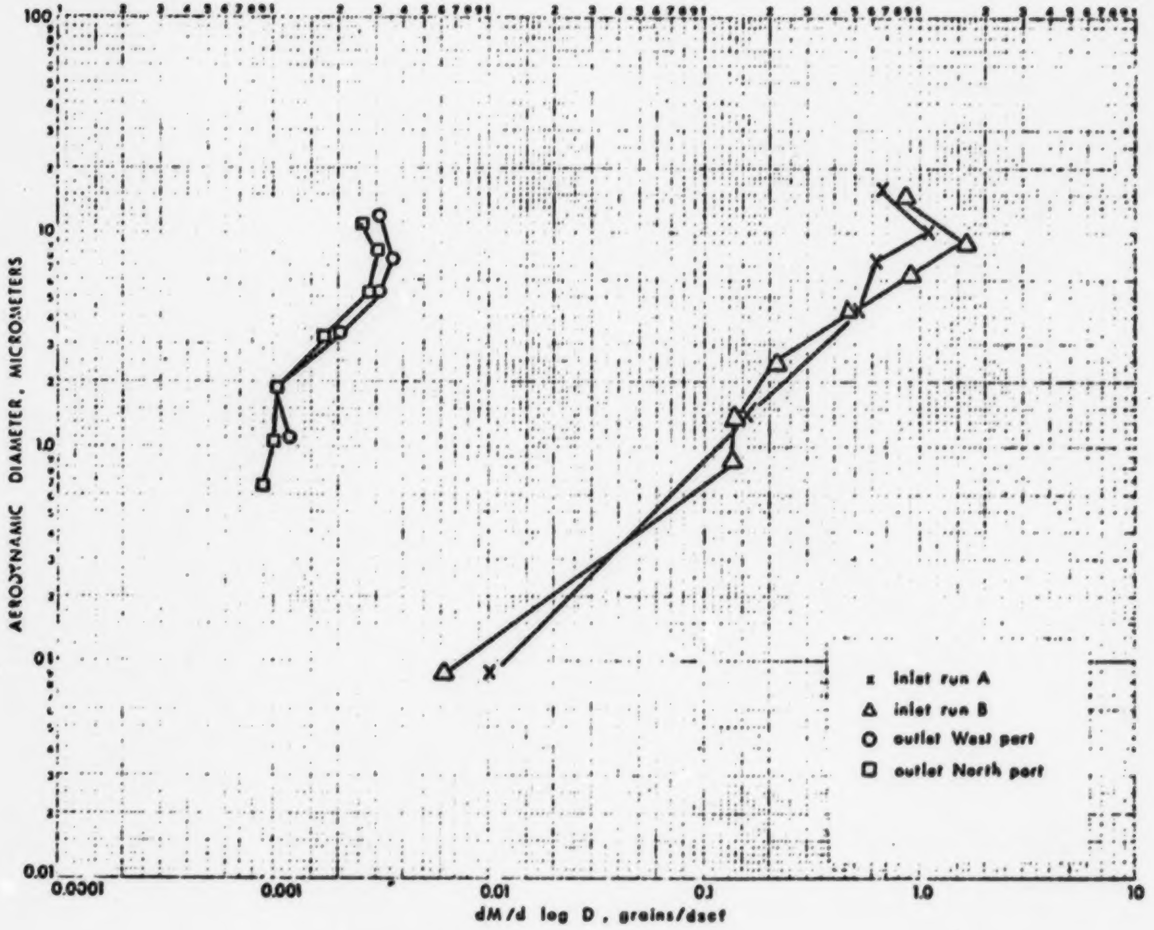

Figure 51. Differential particle size distributions determined by Andersen Impactors for Run 11

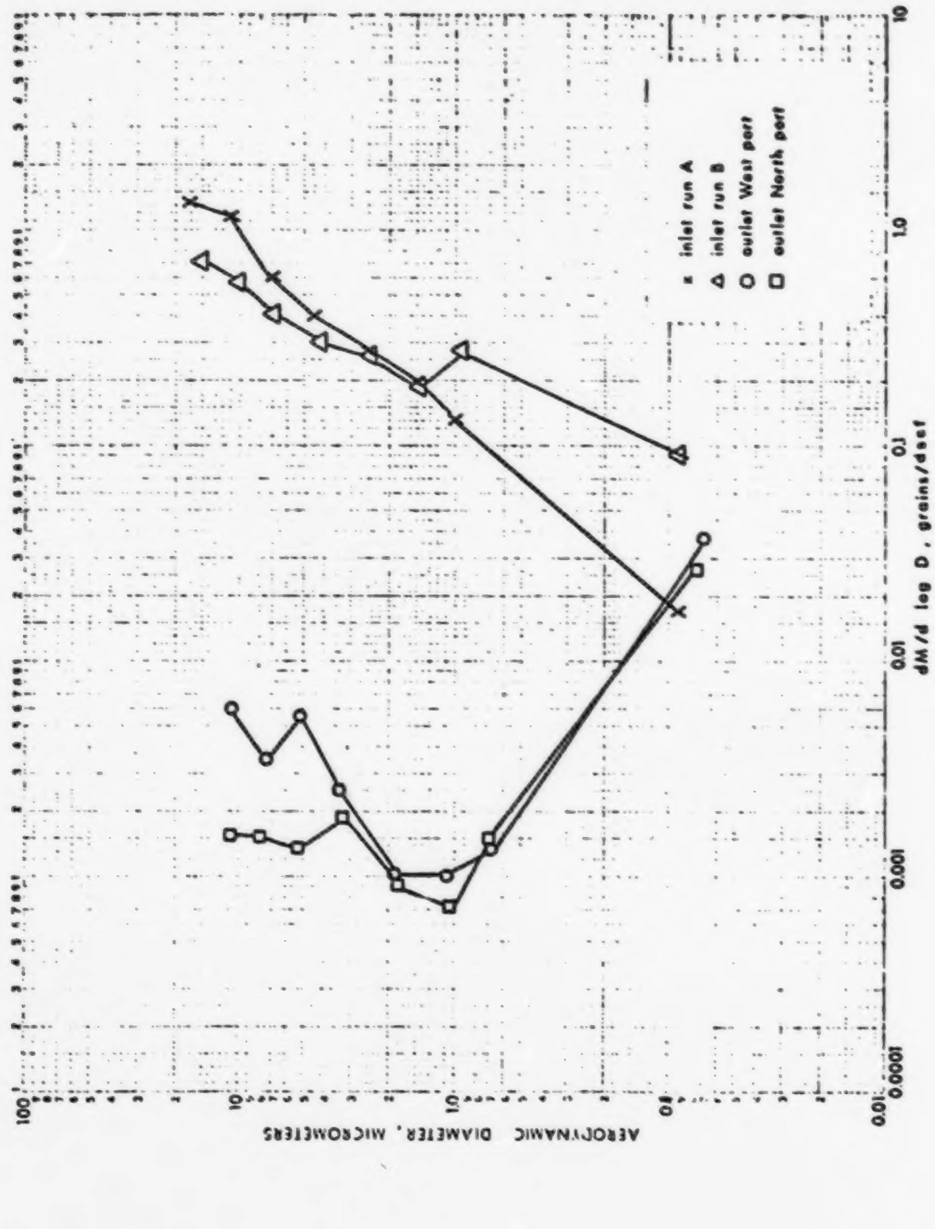

Figure 52. Differential particle size distributions determined by Andersen Impactors for Run 12

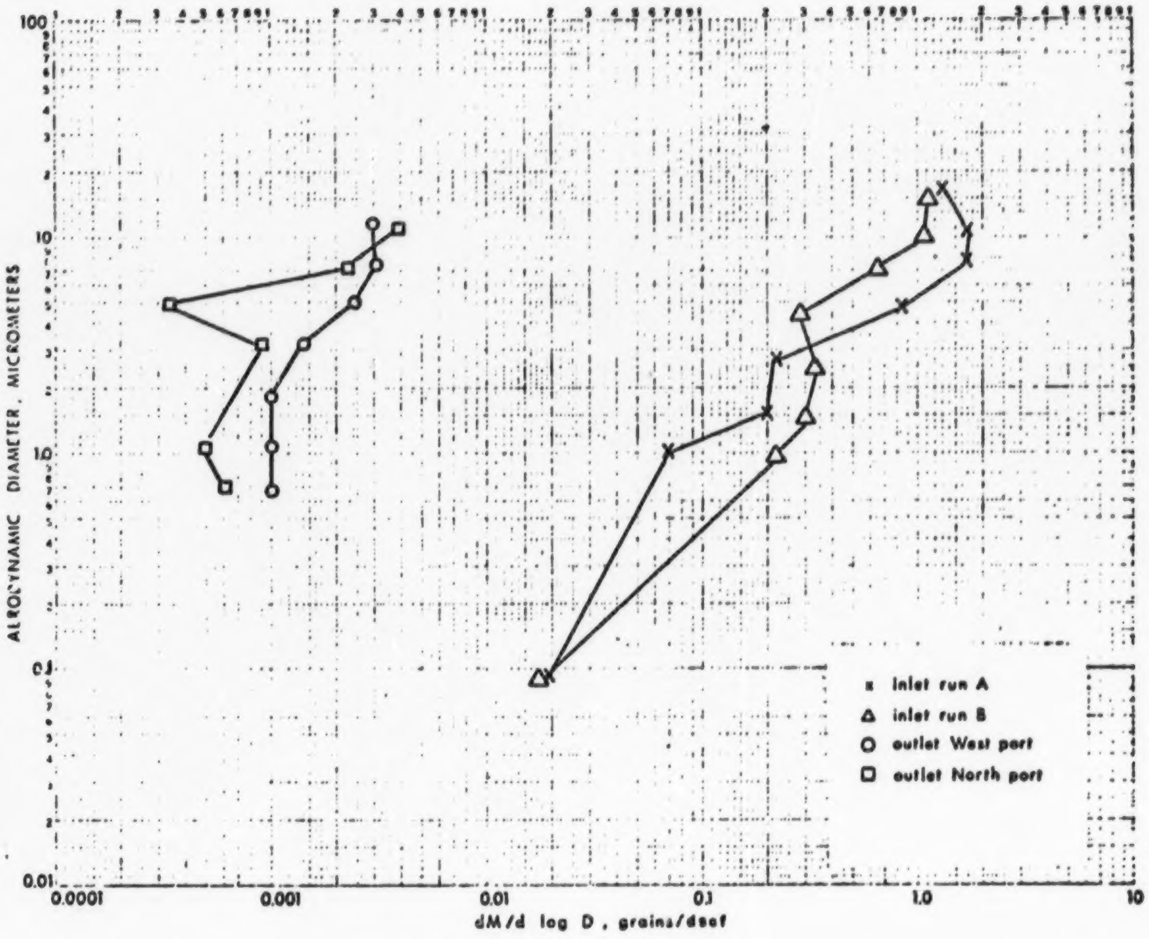

Figure 53. Differential particle size distributions determined by Andersen Impactors for Run 13

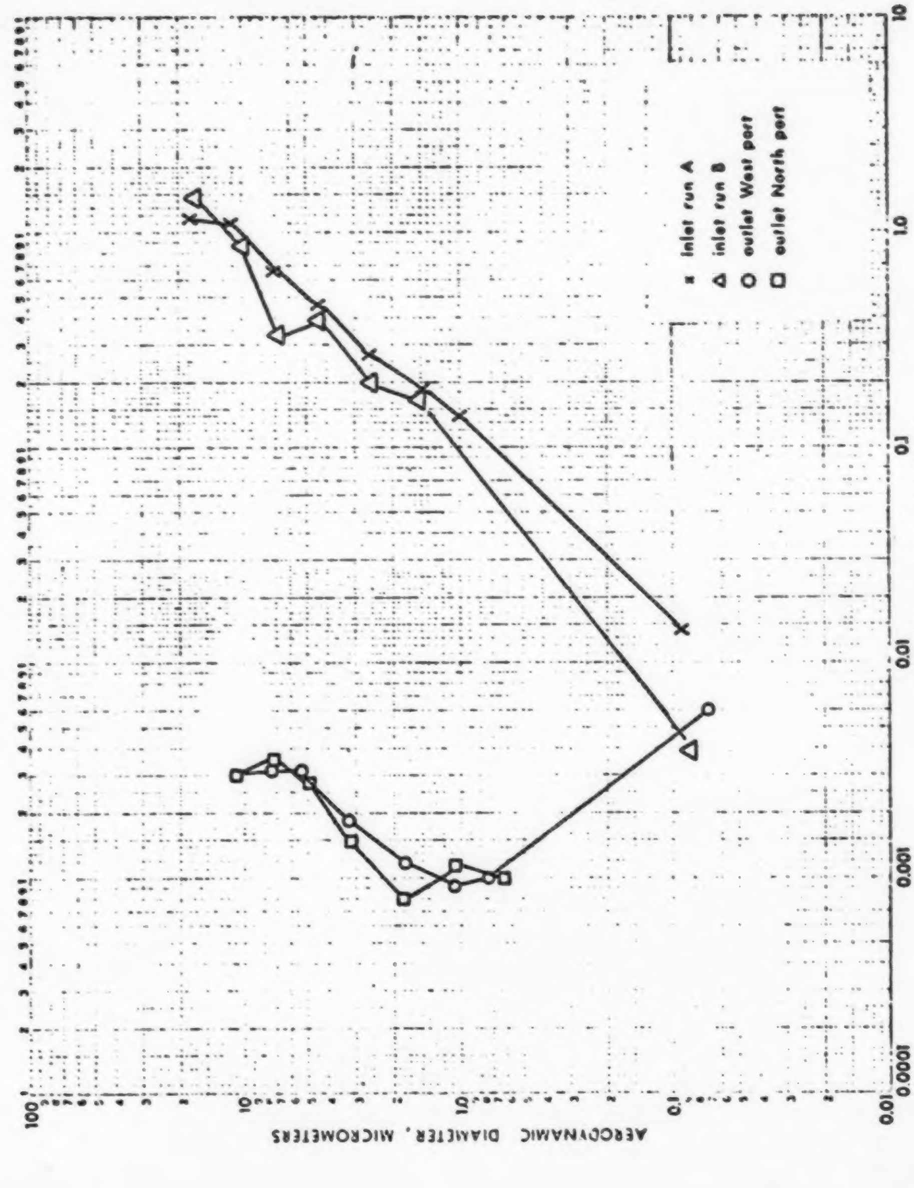

Figure 54. Differential particle size distributions determined by Andersen Impactors for Run 14

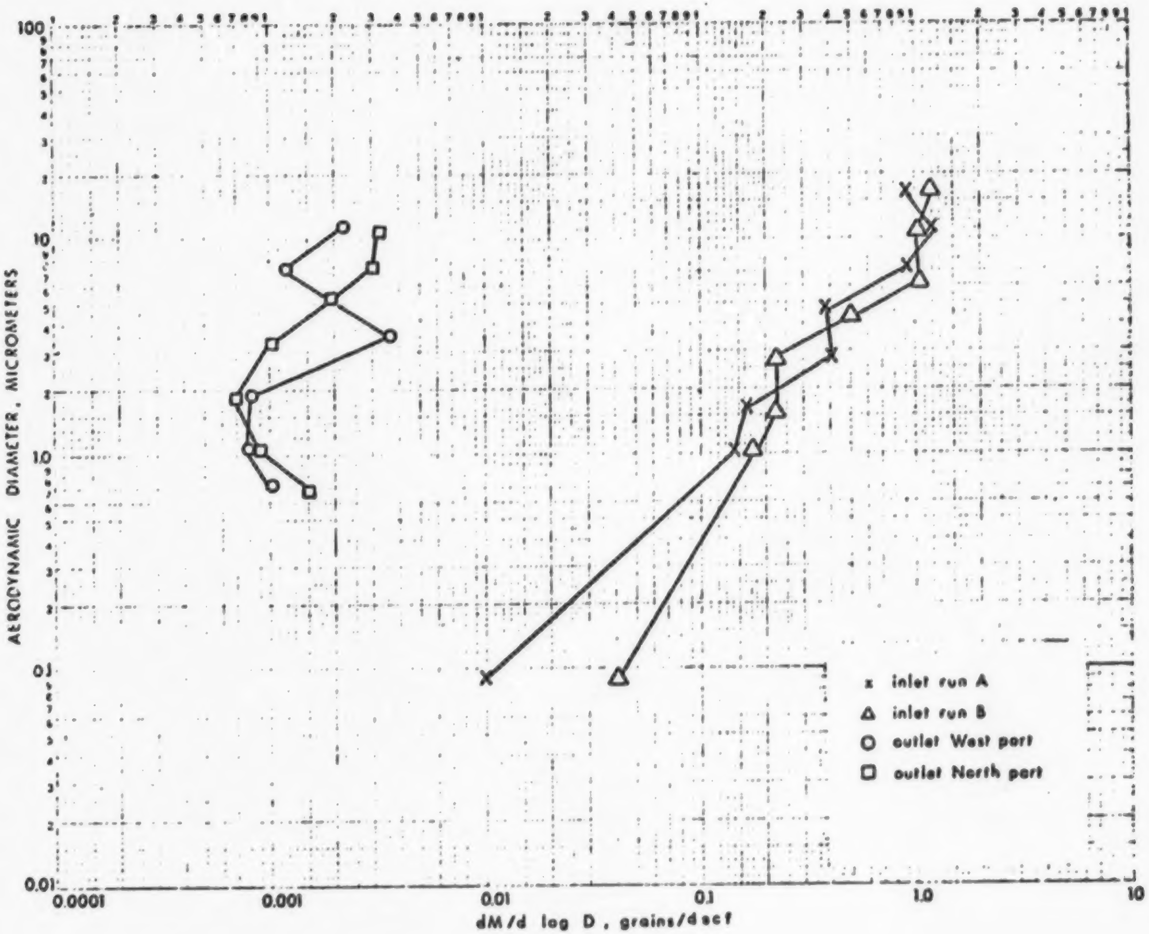

Figure 55. Differential particle size distributions determined by Andersen Impactors for Run 15

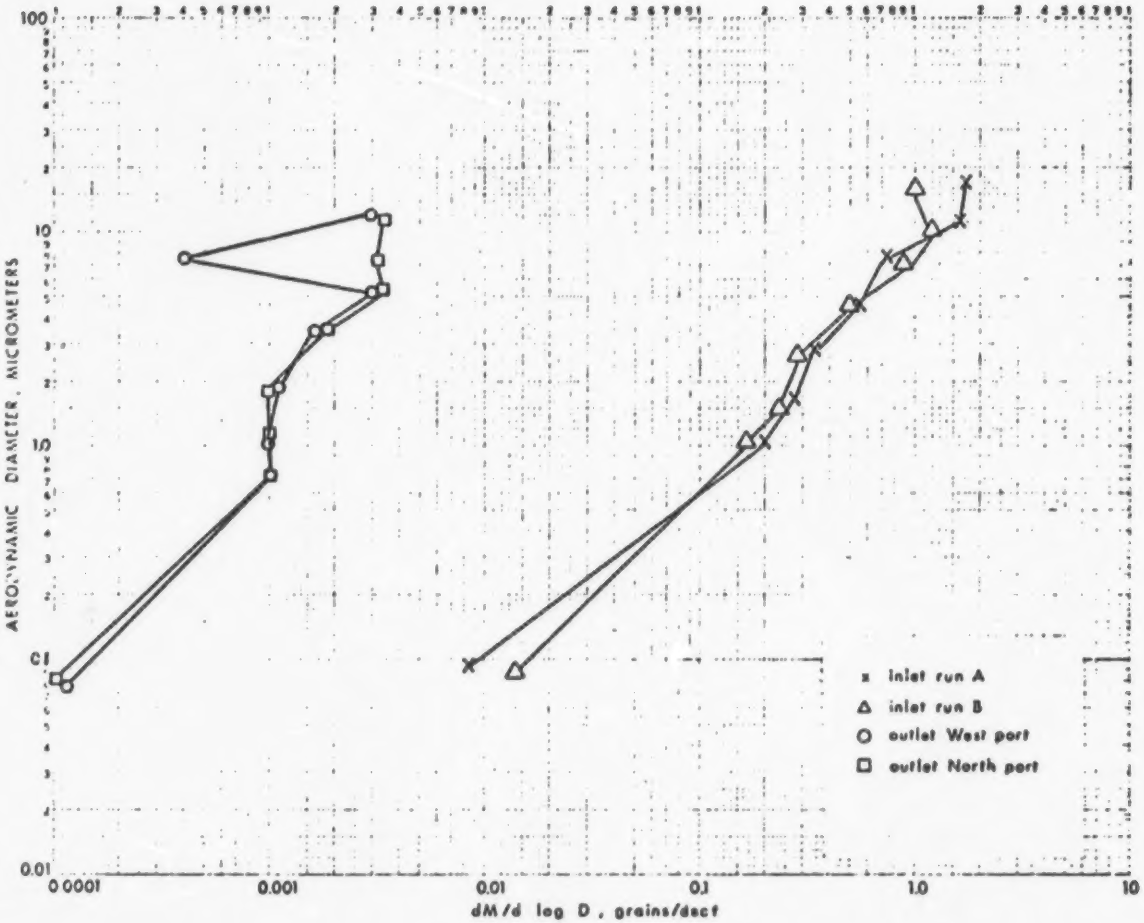

Figure 56. Differential particle size distributions determined by Andersen Impactors for Run 16

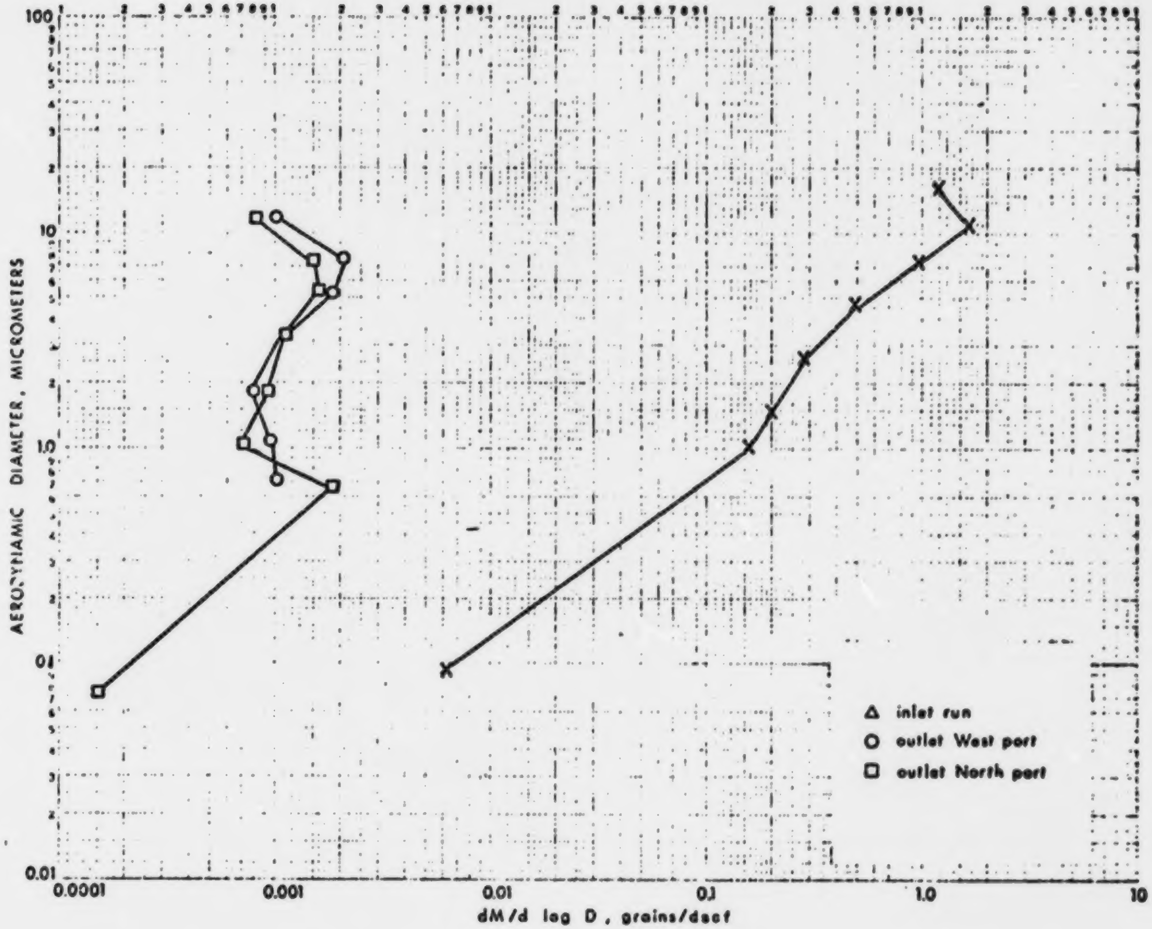

Figure 57. Differential particle size distributions determined by Andersen Impactors for Run 17

Reproduced from best available copy.

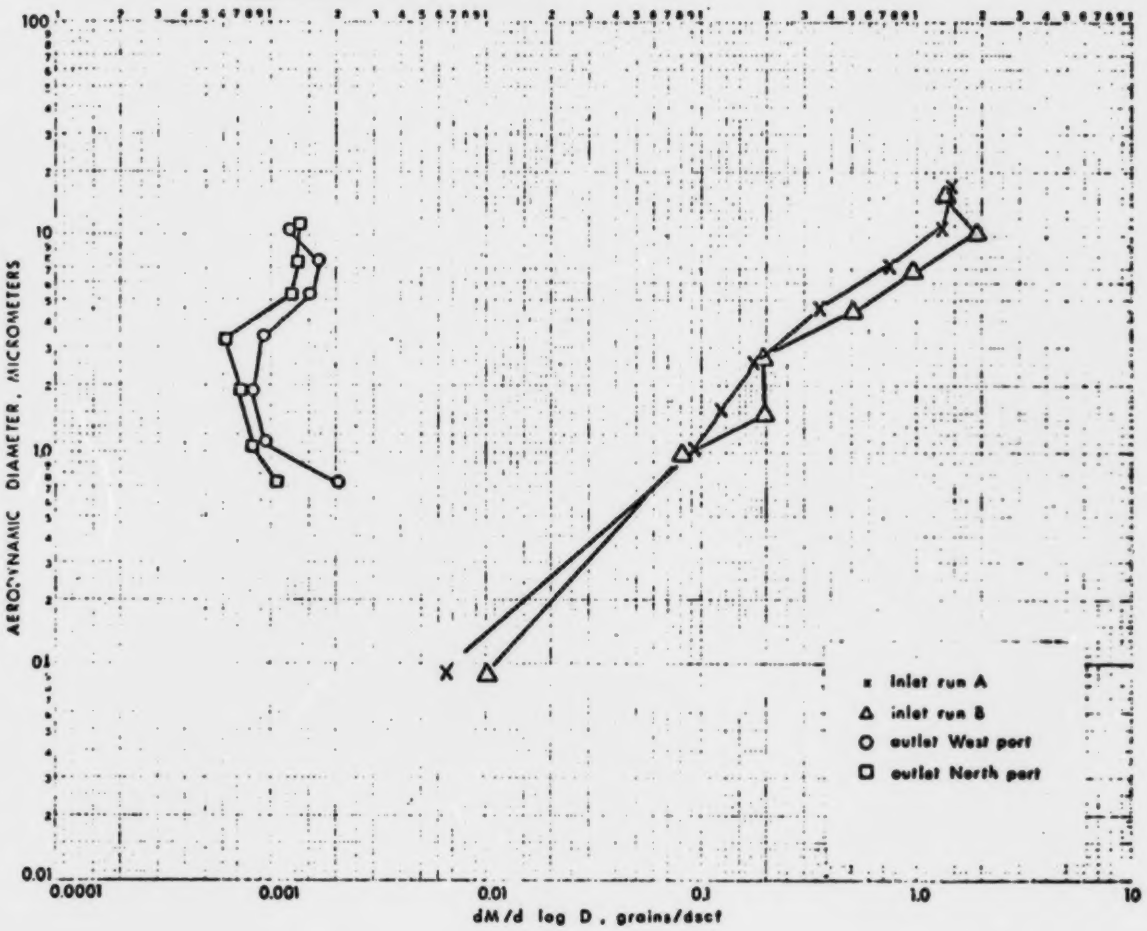

Figure 58. Differential particle size distributions determined by Andersen Impactors for Run 18

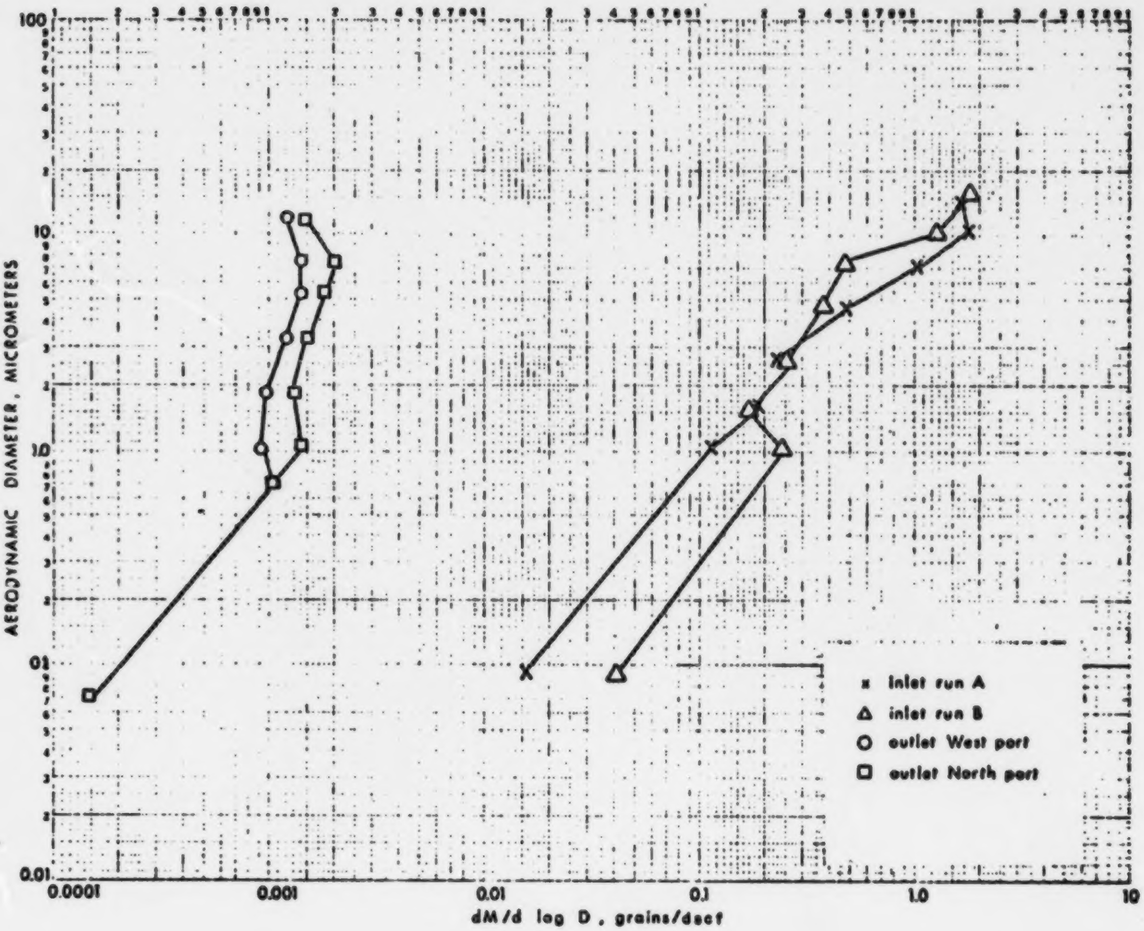

Figure 59. Differential particle size distributions determined by Andersen Impactors for Run 19

Reproduced from best available copy.

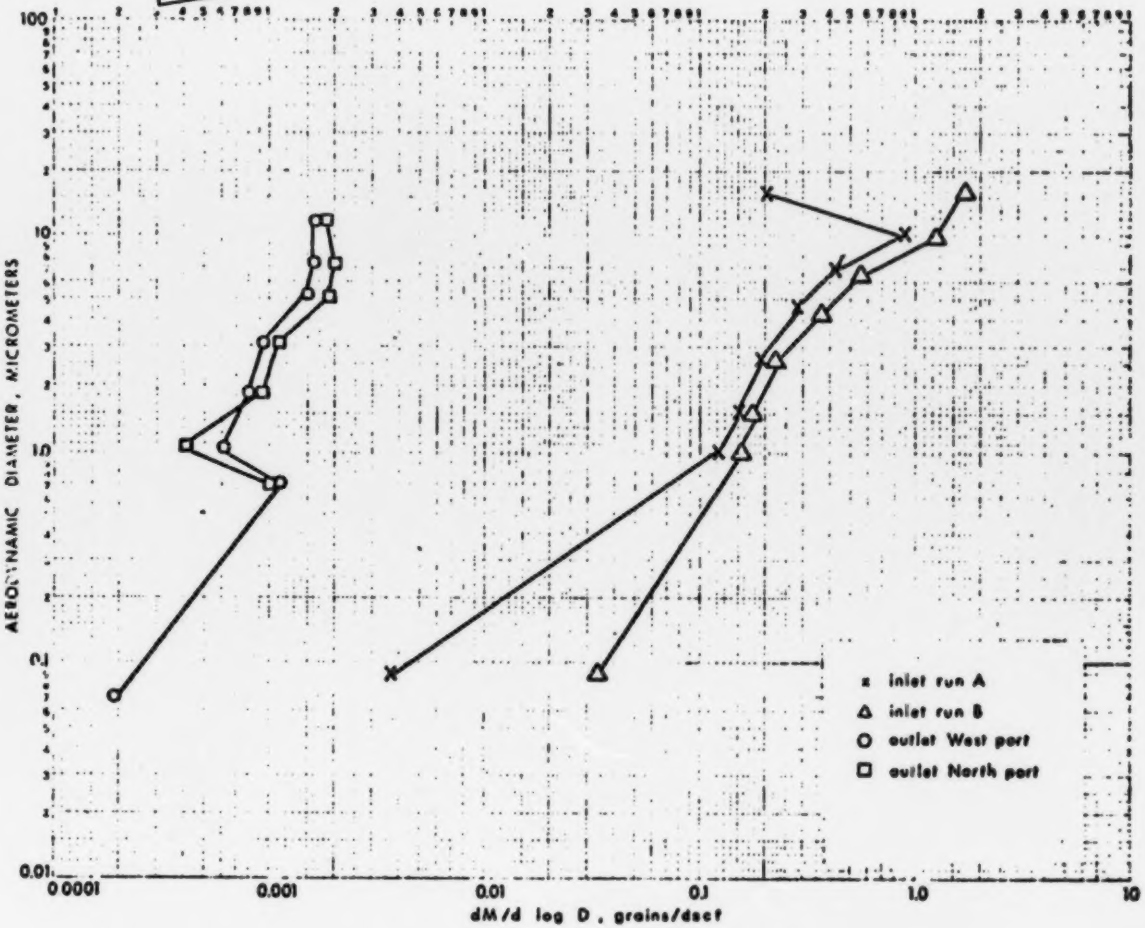

Figure 60. Differential particle size distributions determined by Andersen Impactors for Run 20

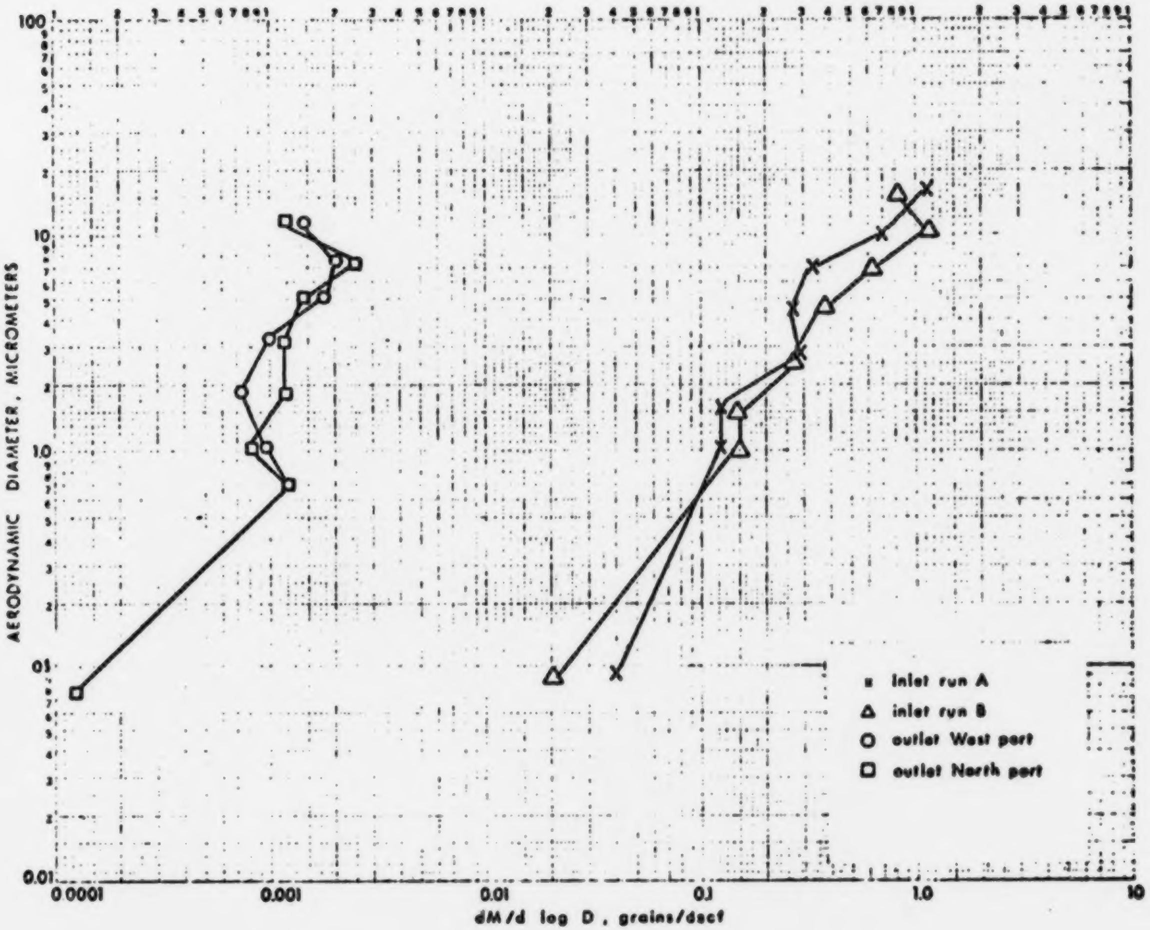

Figure 61. Differential particle size distributions determined by Andersen Impactors for Run 21

Reproduced from
best available copy.

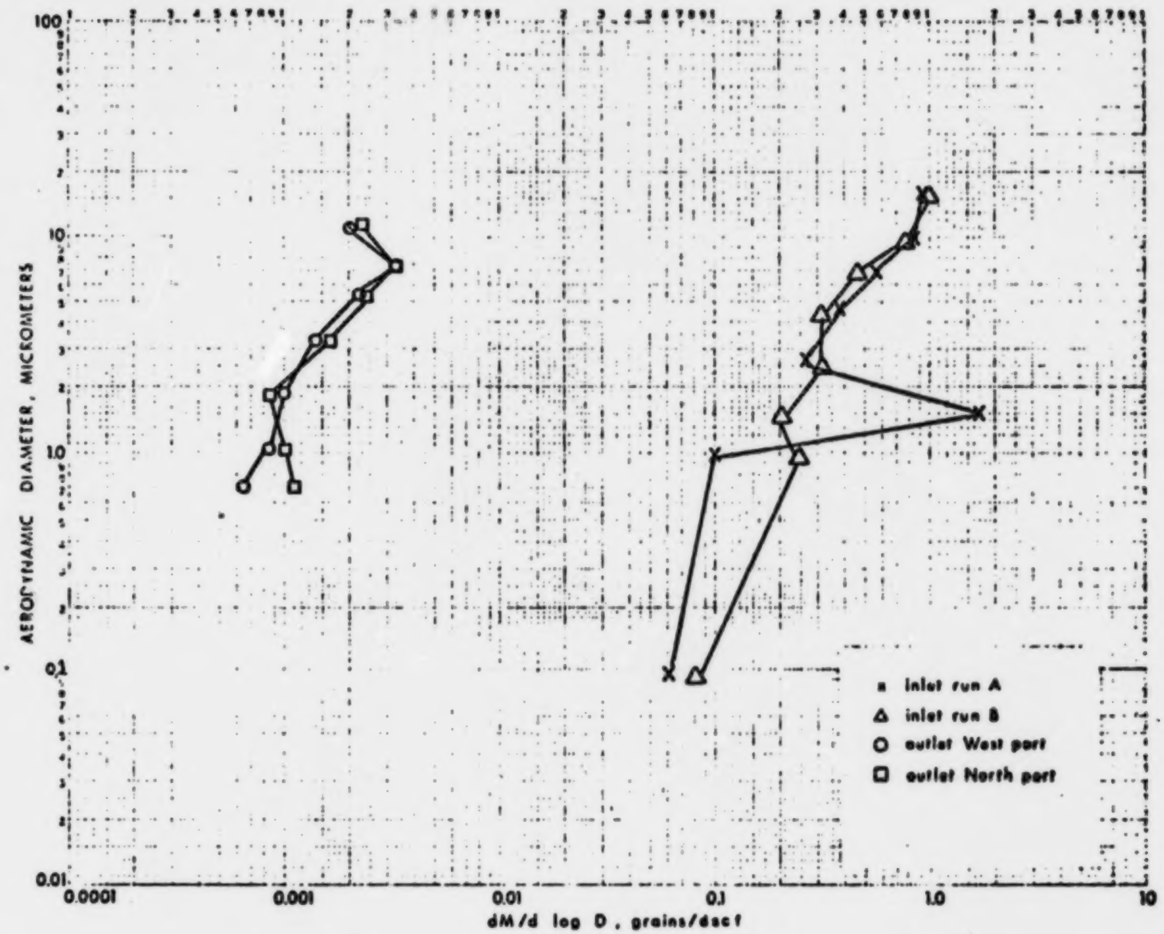

Figure 62. Differential particle size distributions determined by Andersen Impactors for Run 22

APPENDIX C

FRACTIONAL EFFICIENCY/PENETRATION CURVES

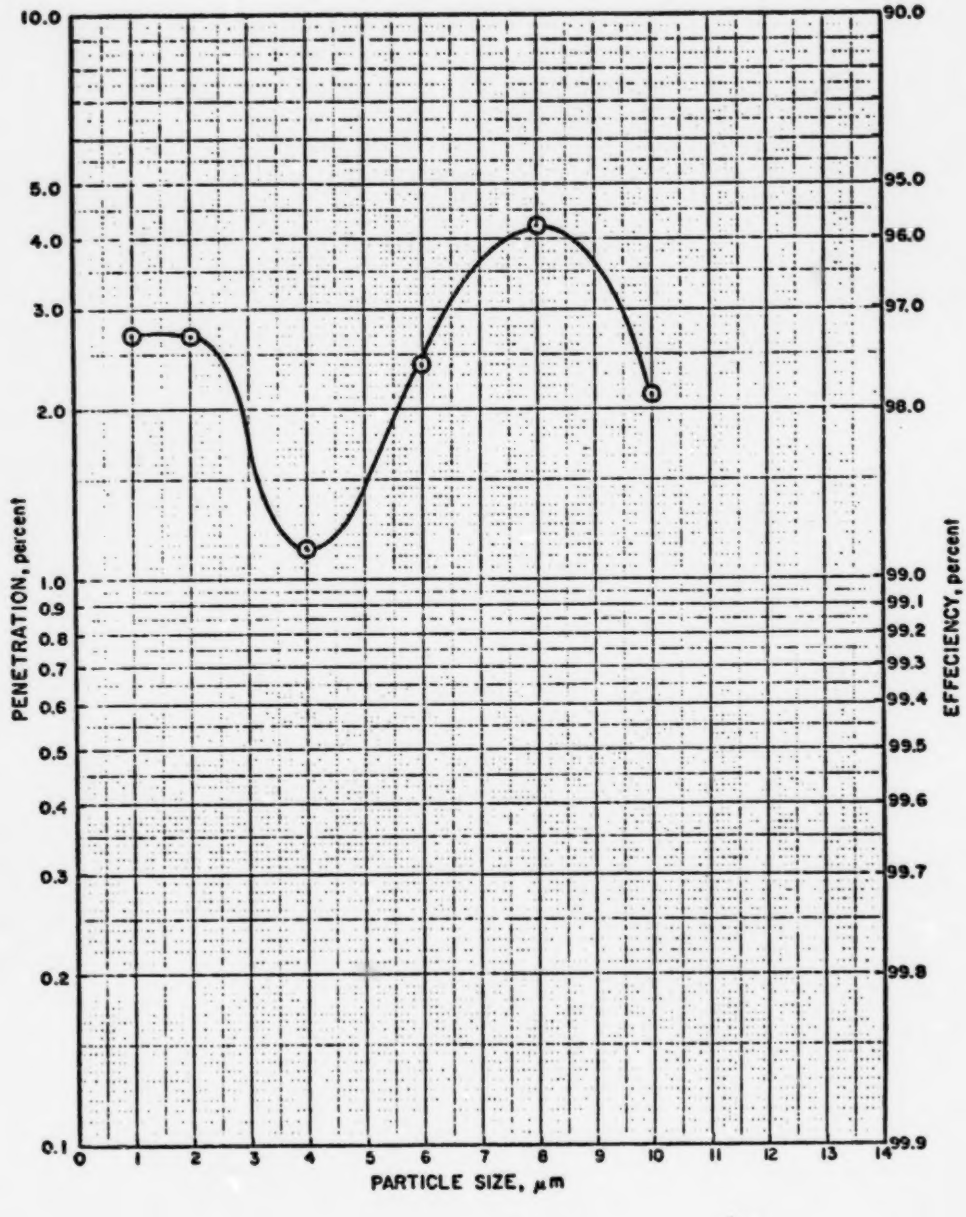

Figure 63. Penetration/efficiency as a function of size for Run 1

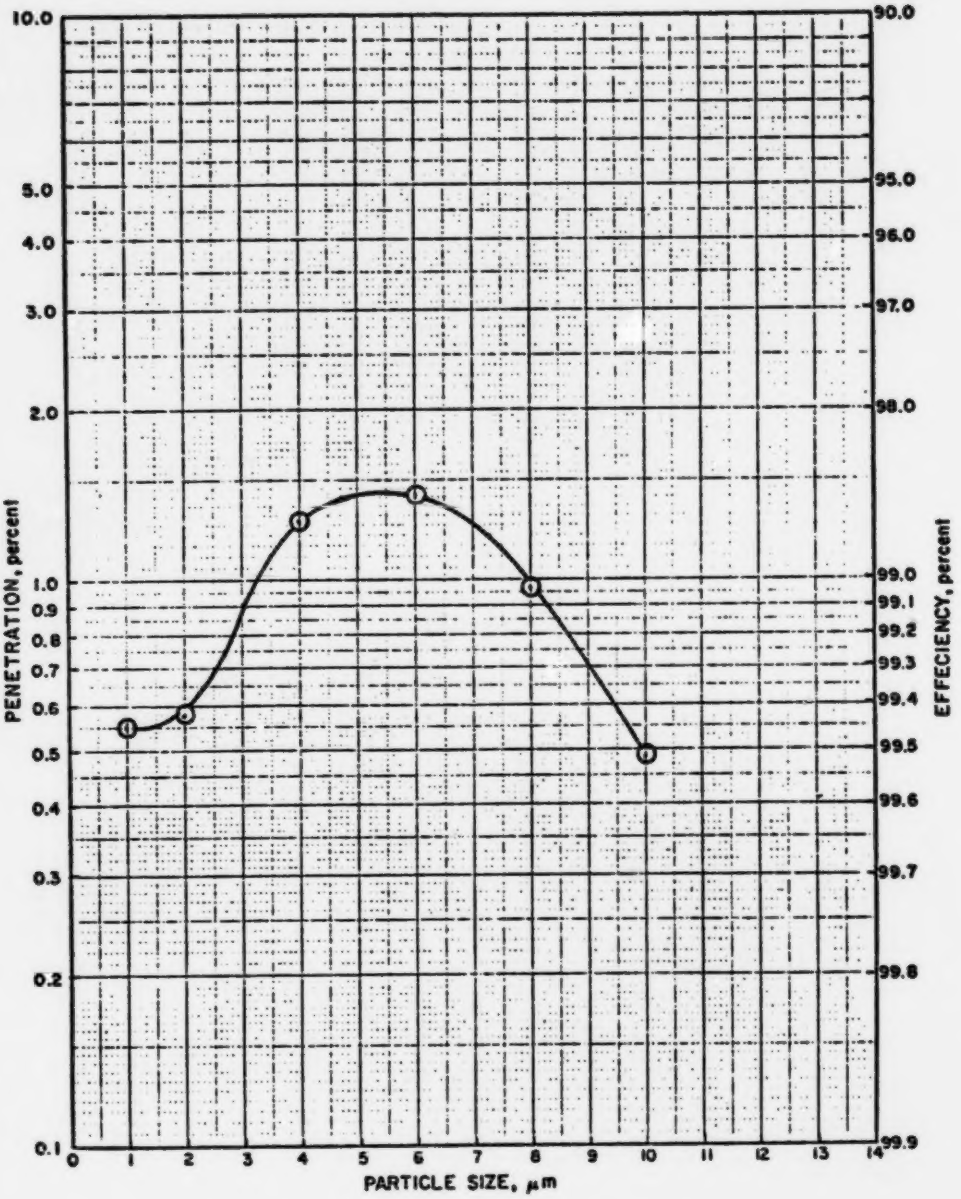

Figure 64. Penetration/efficiency as a function of size for Run 2

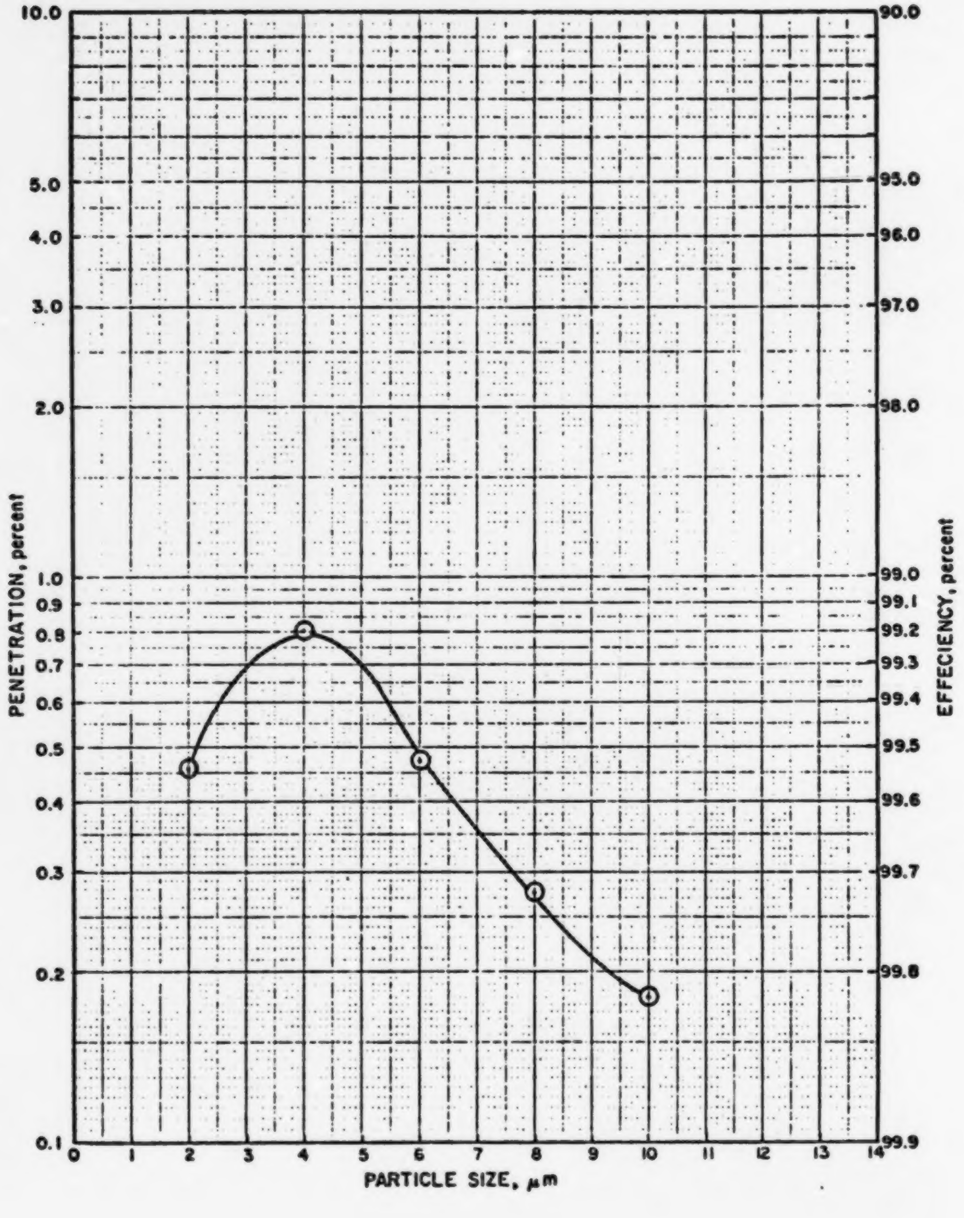

Figure 65. Penetration/efficiency as a function of size for Run 3

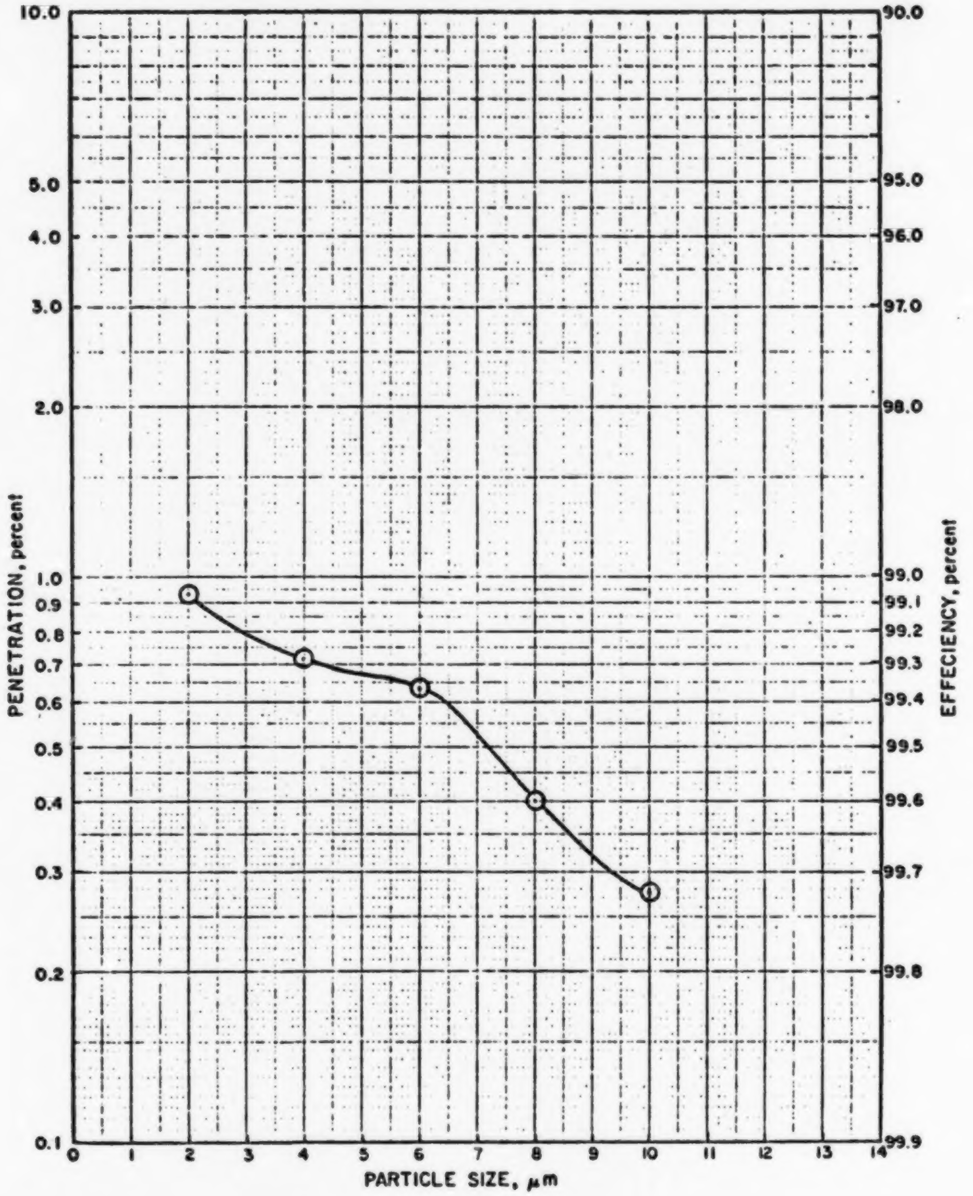

Figure 66. Penetration/efficiency as a function of size for Run 4

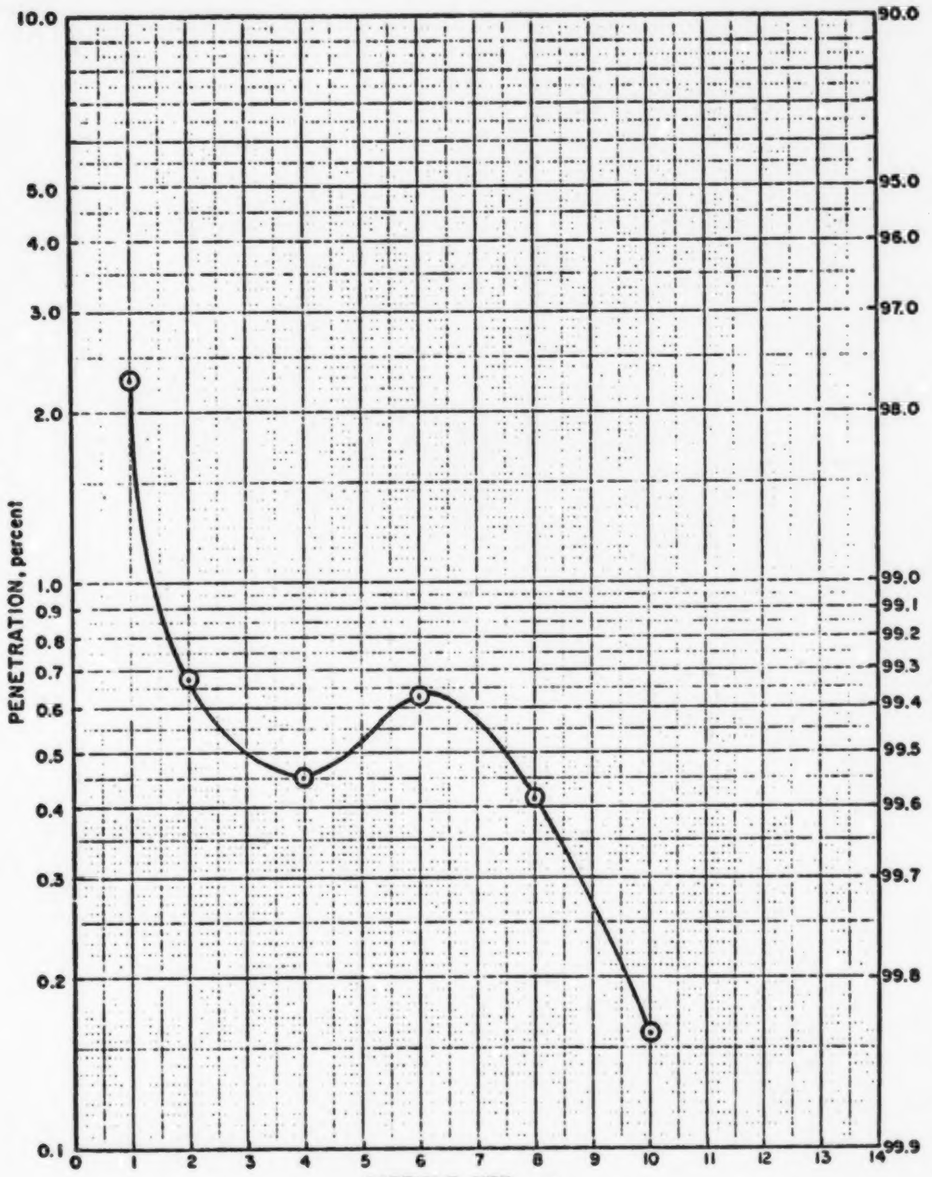

Figure 67. Penetration/efficiency as a function of size for Run 5

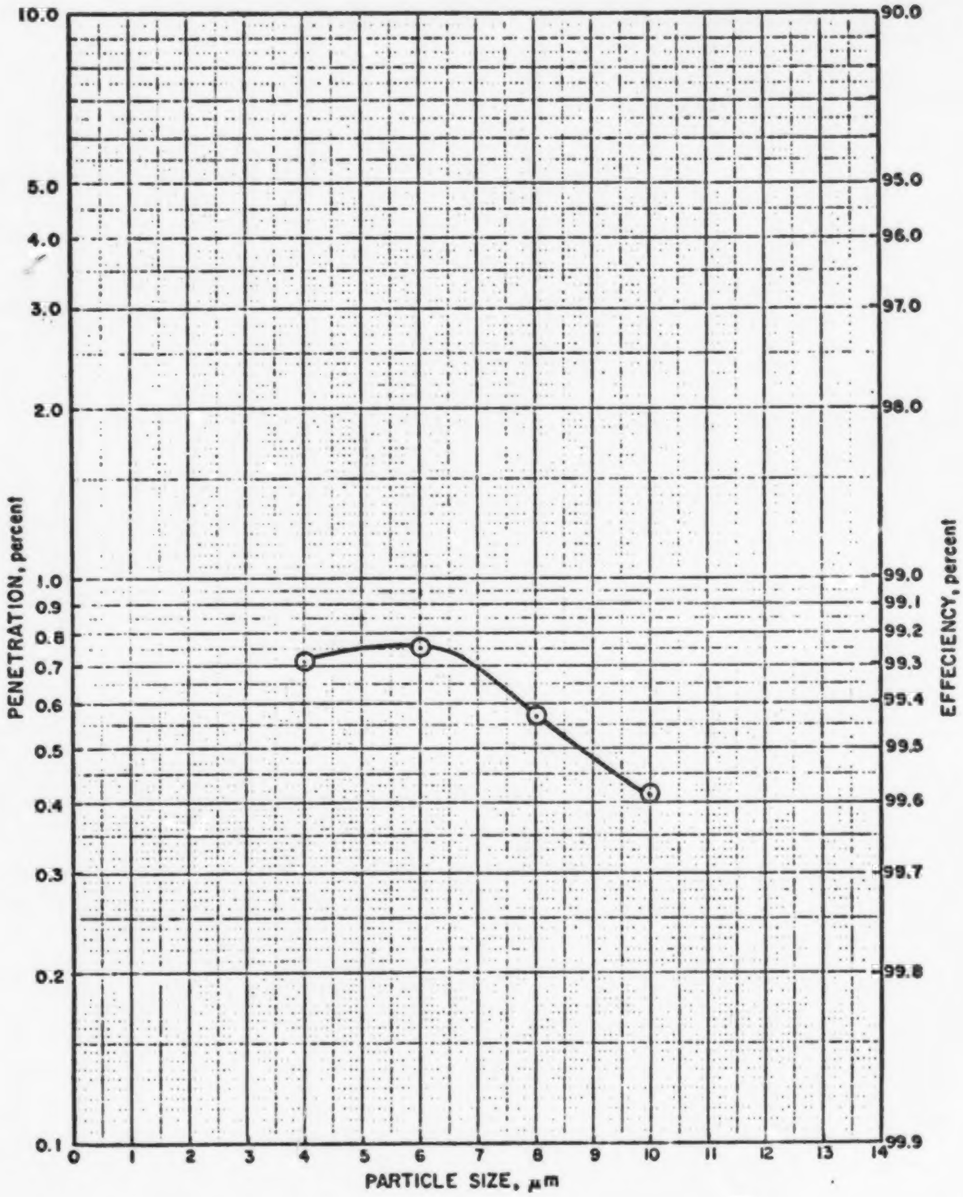

Figure 68. Penetration/efficiency as a function of size for Run 6

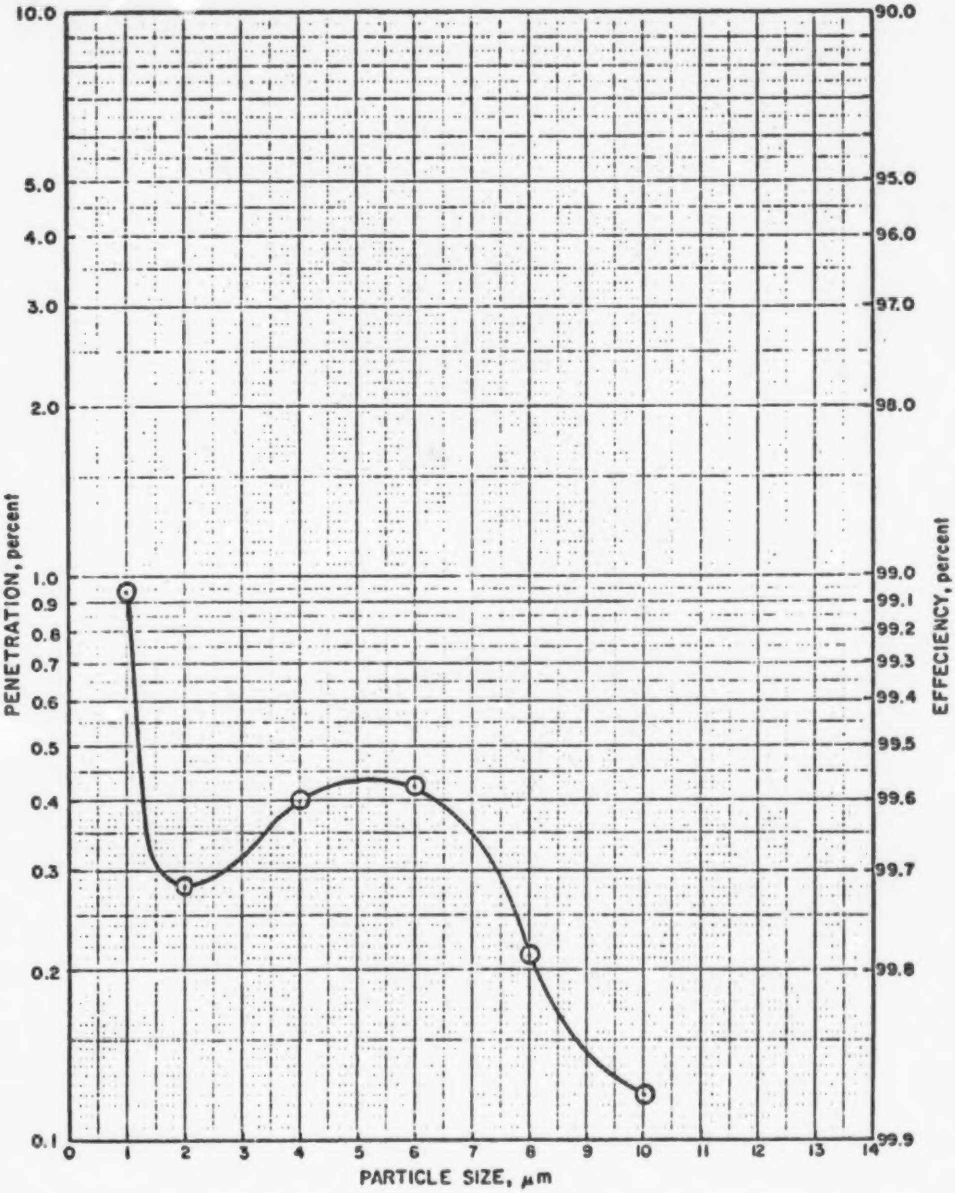

Figure 69. Penetration/efficiency as a function of size for Run 7

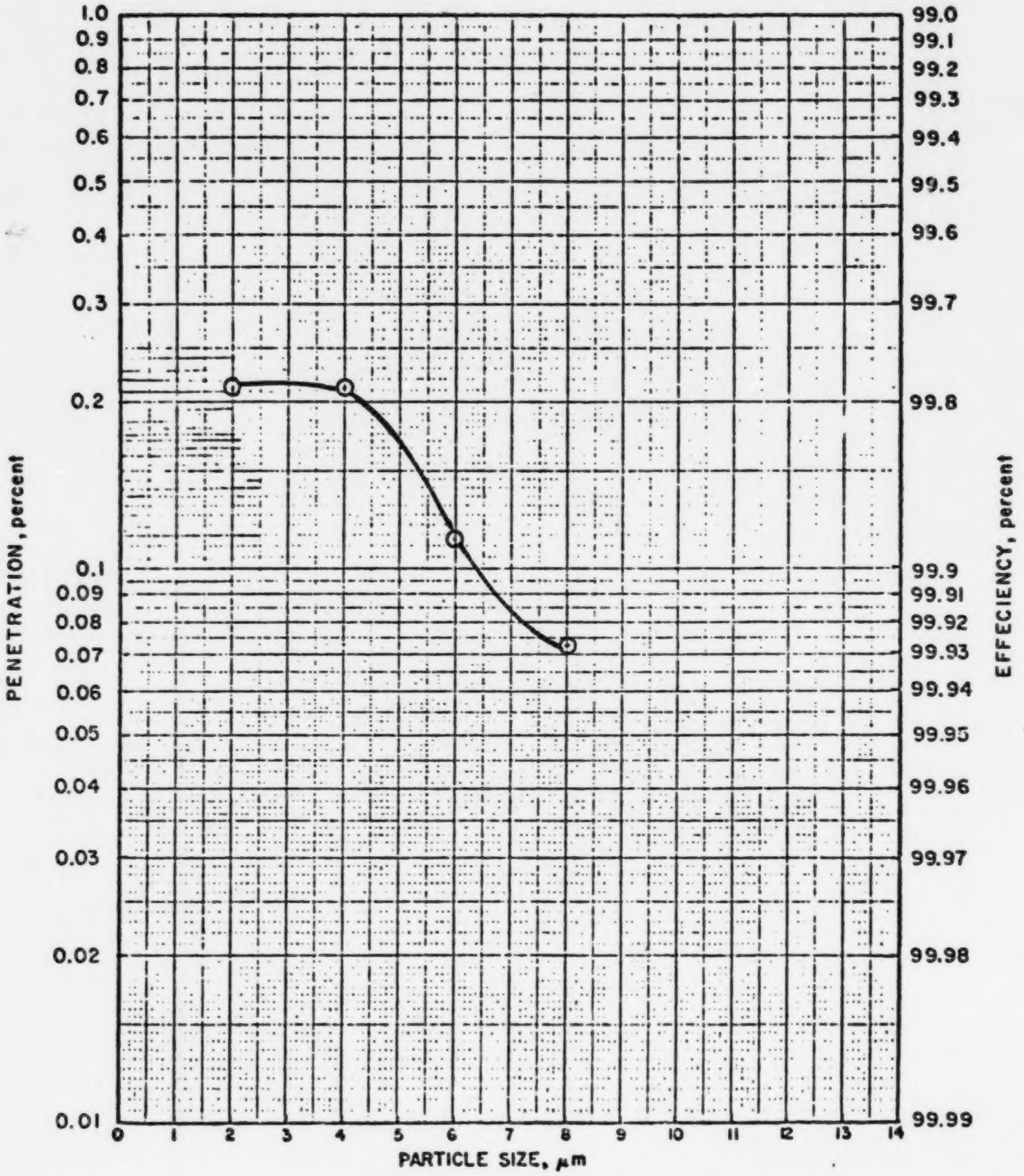

Figure 70. Penetration/efficiency as a function of size for Run 8

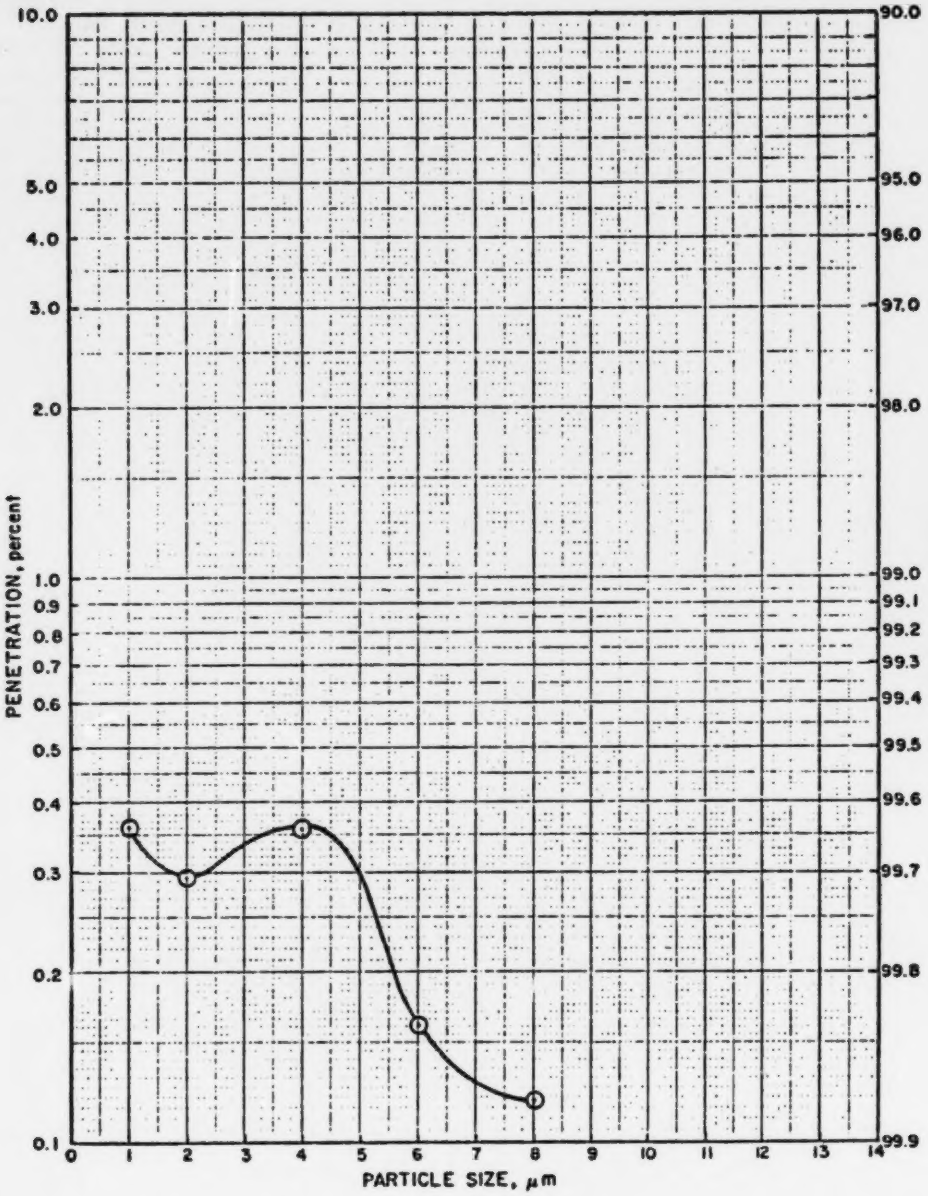

Figure 71. Penetration/efficiency as a function of size for Run 9

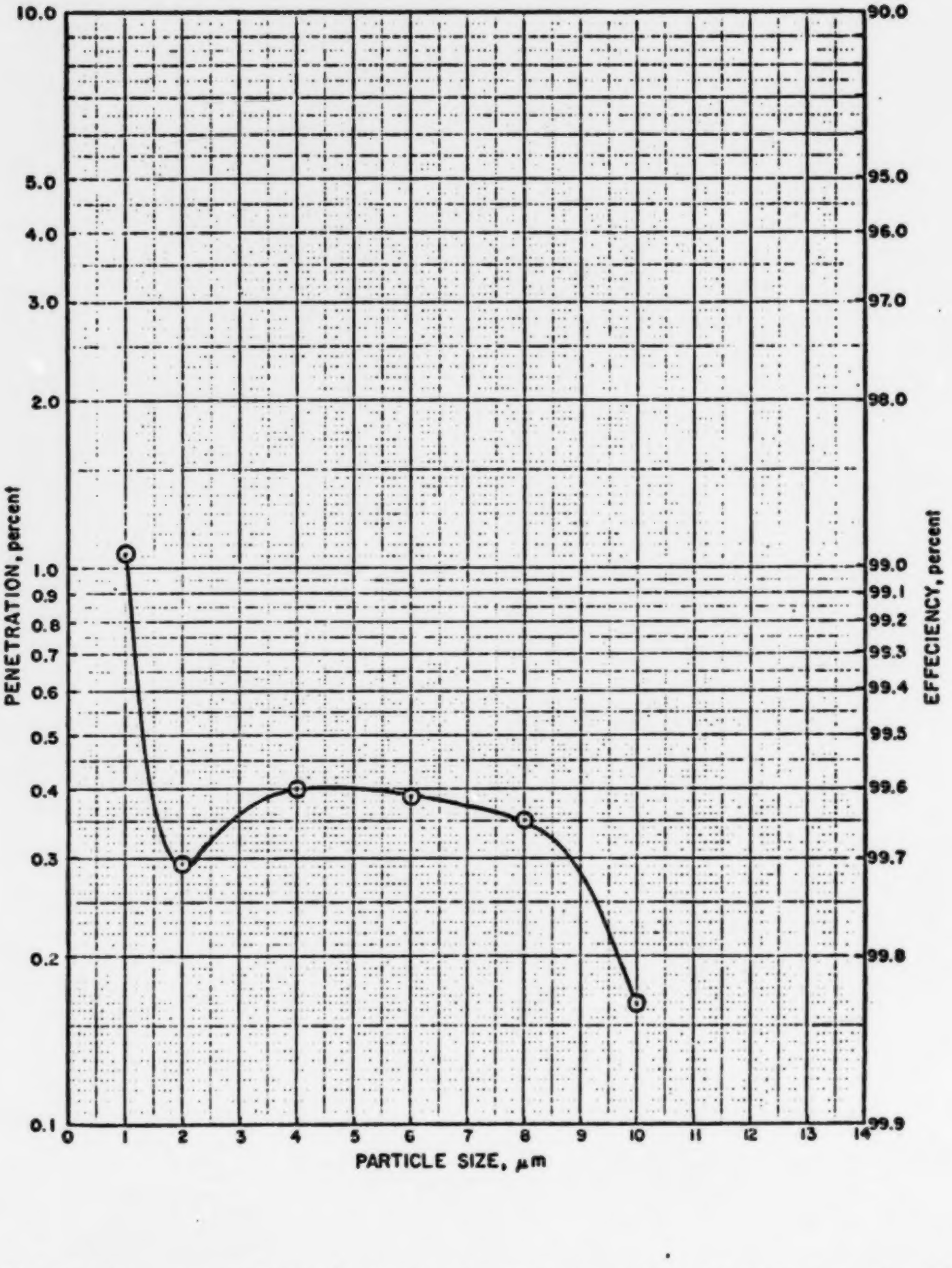

Figure 72. Penetration/efficiency as a function of size for Run 10

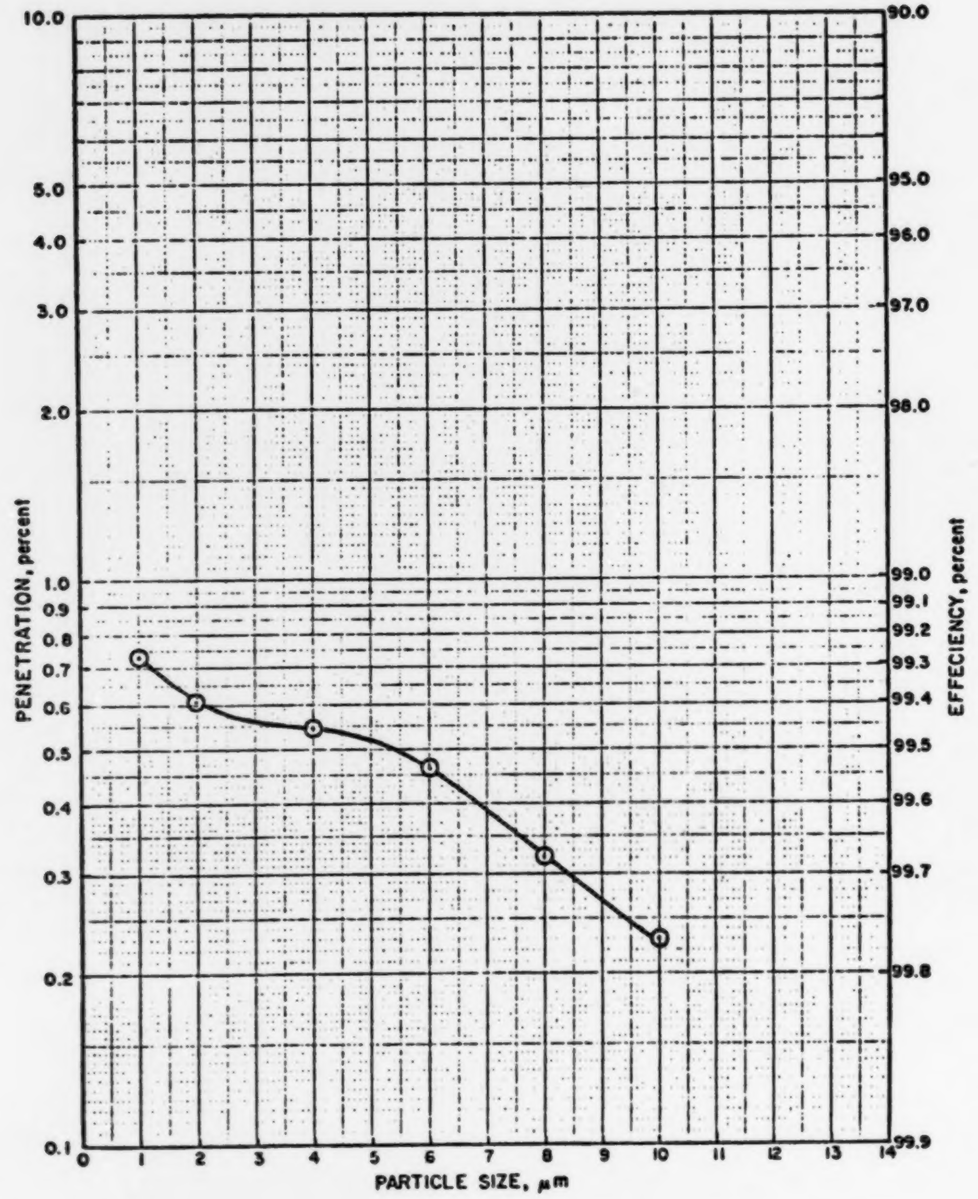

Figure 73. Penetration/efficiency as a function of size for Run 11

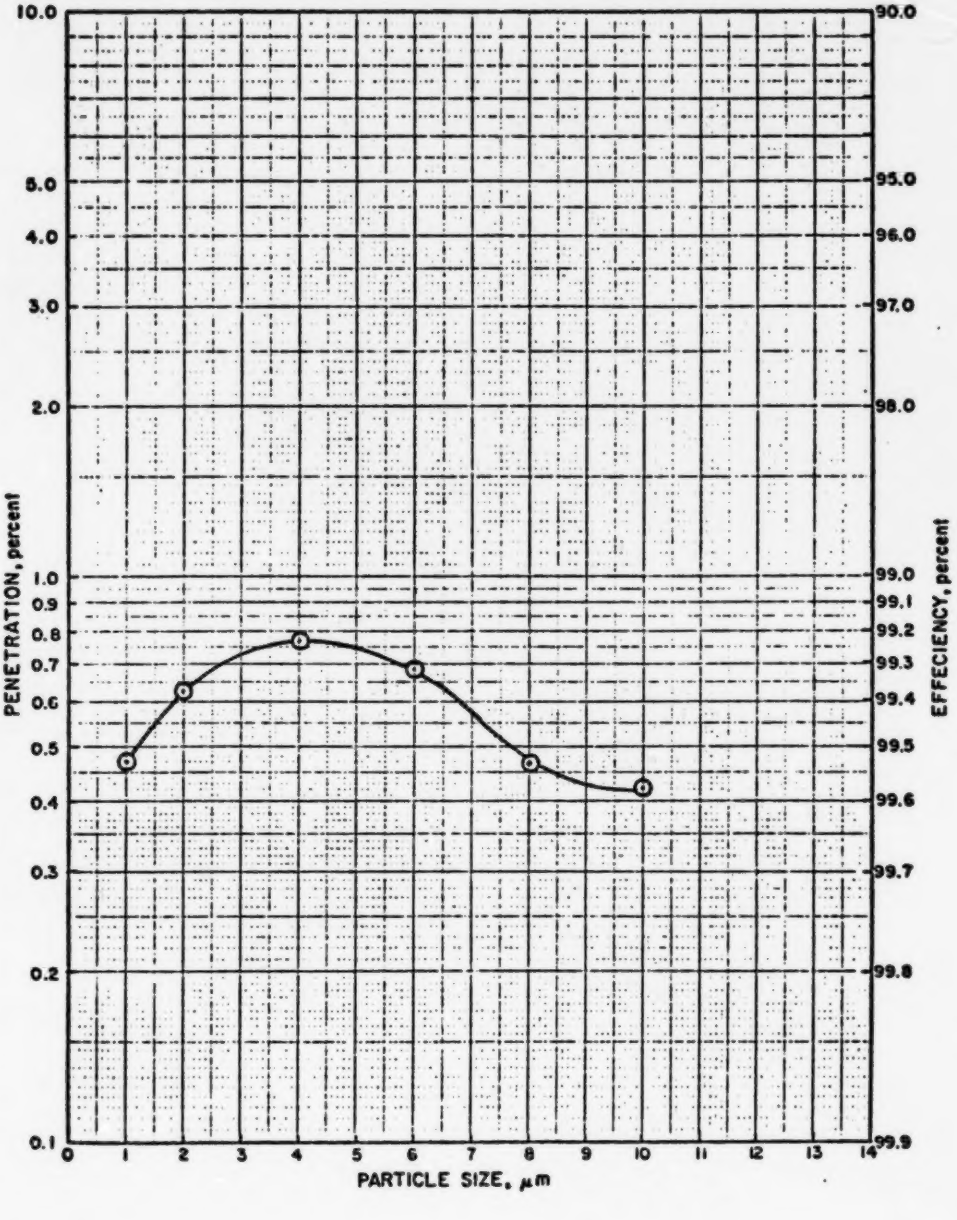

Figure 74. Penetration/efficiency as a function of size for Run 12

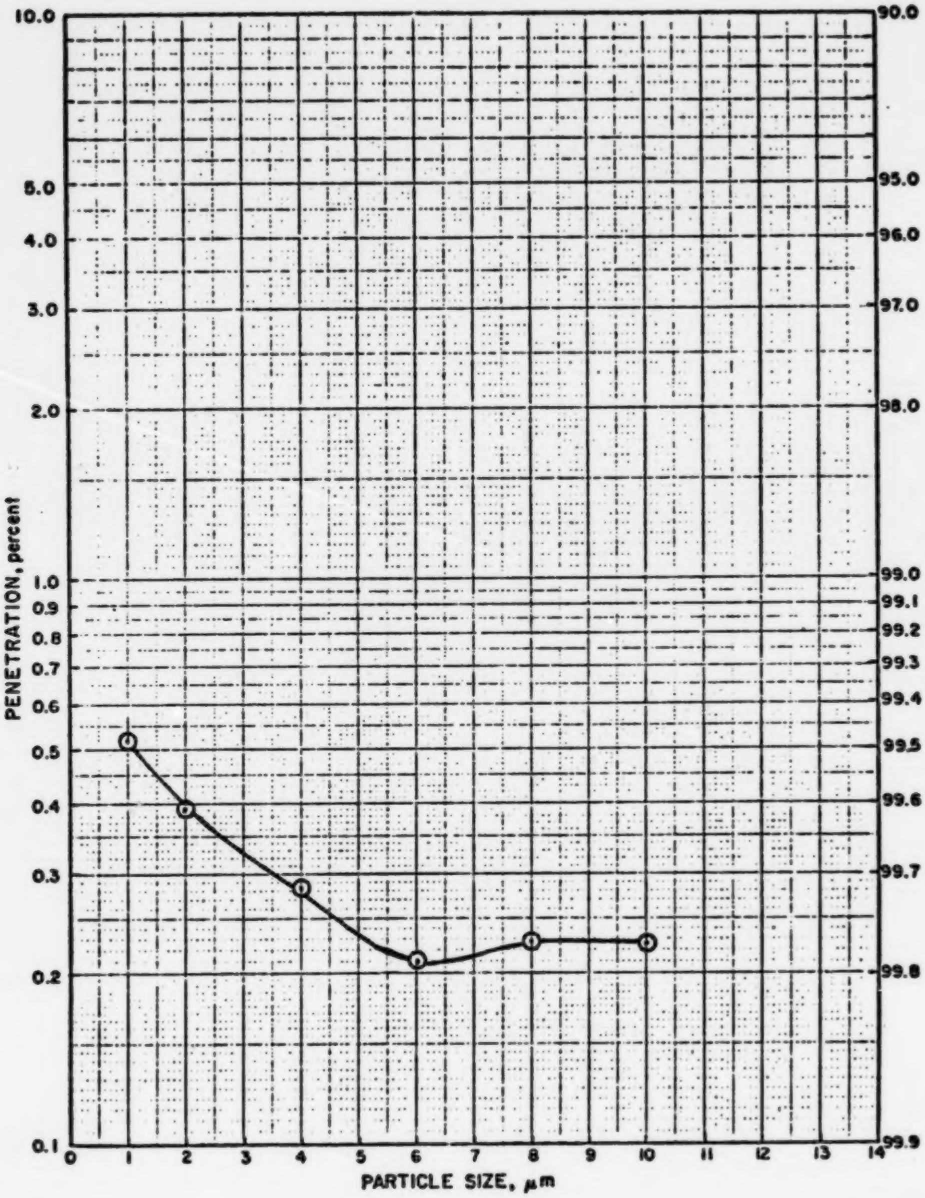

Figure 75. Penetration/efficiency as a function of size for Run 13

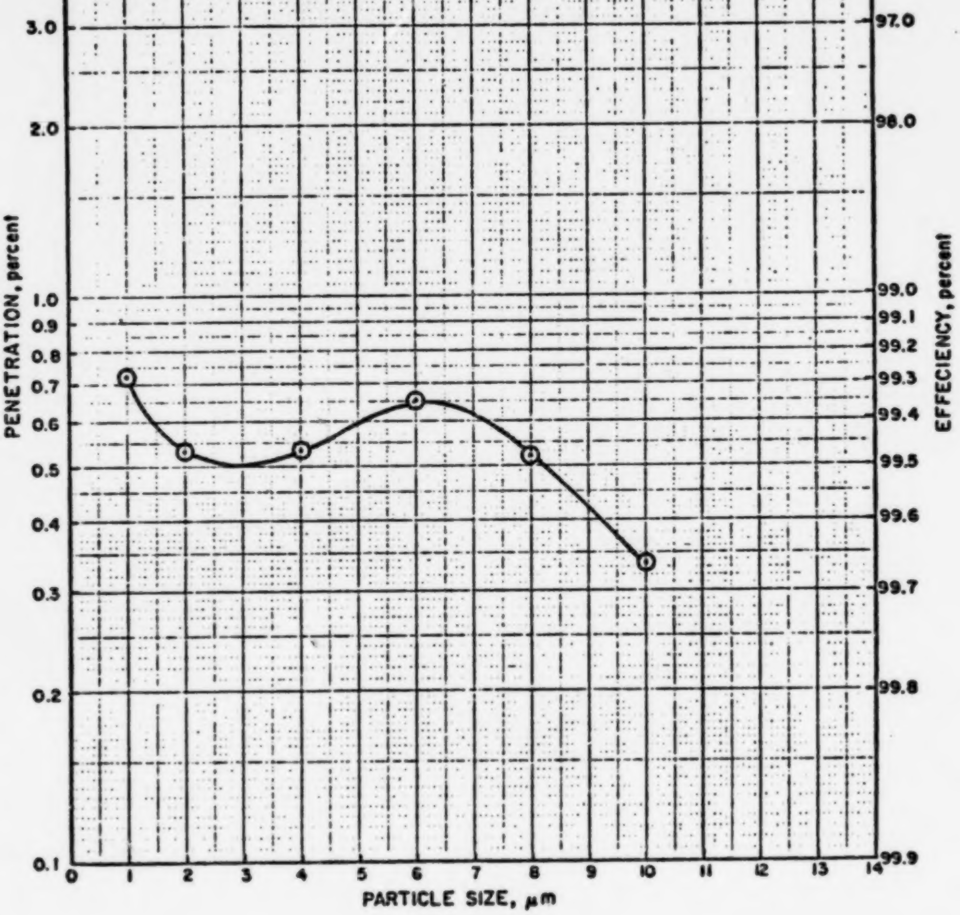

Figure 76. Penetration/efficiency as a function of size for Run 14

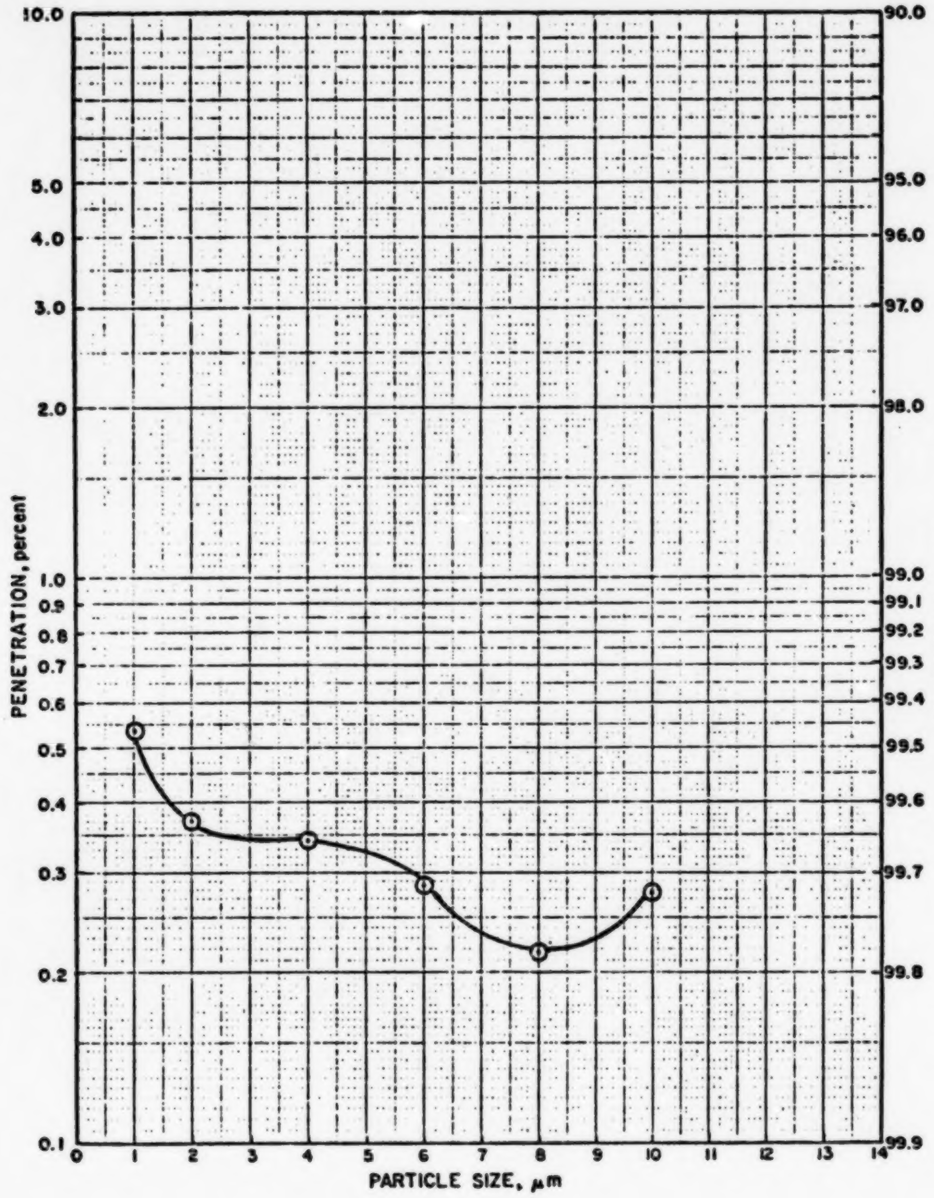

Figure 77. Penetration/efficiency as a function of size for Run 15

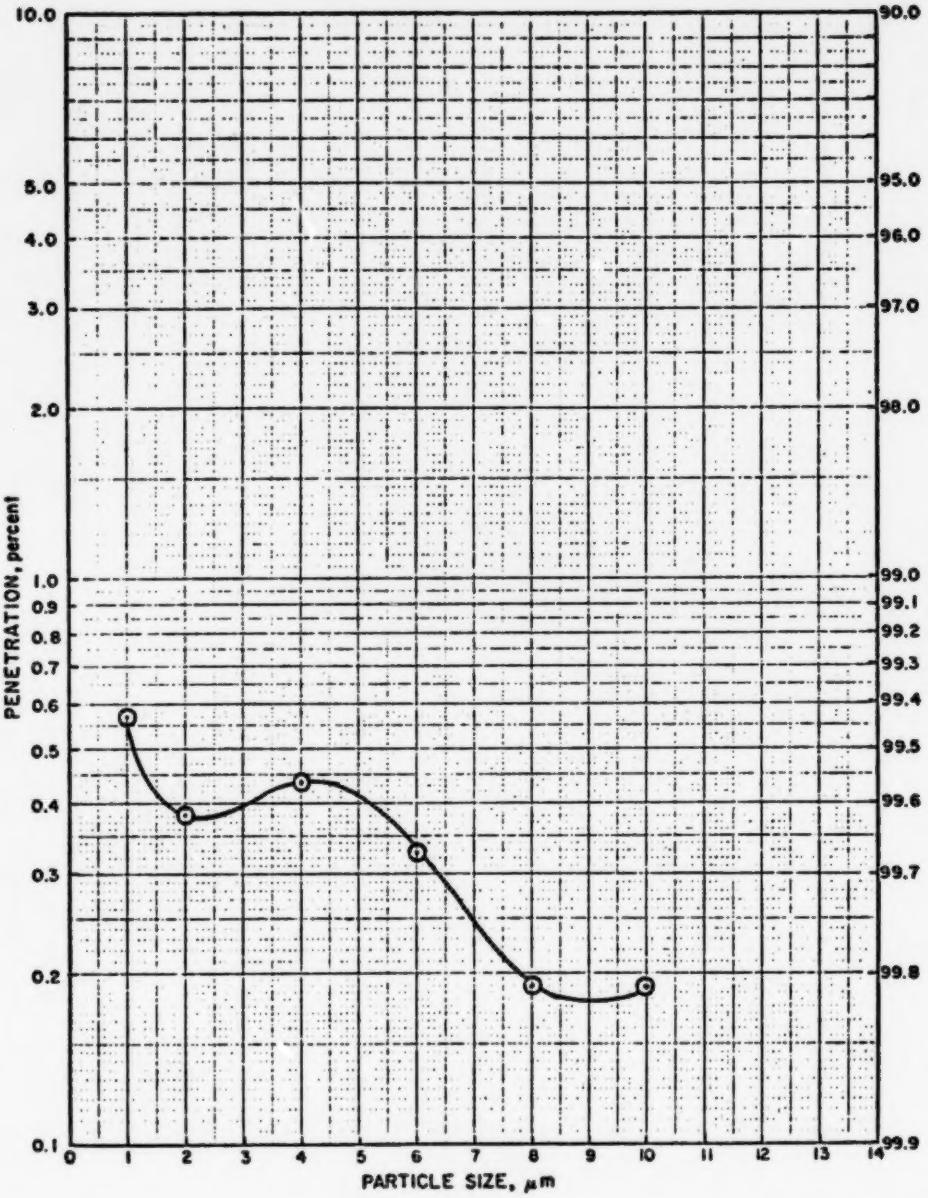

Figure 78. Penetration/efficiency as a function of size for Run 16

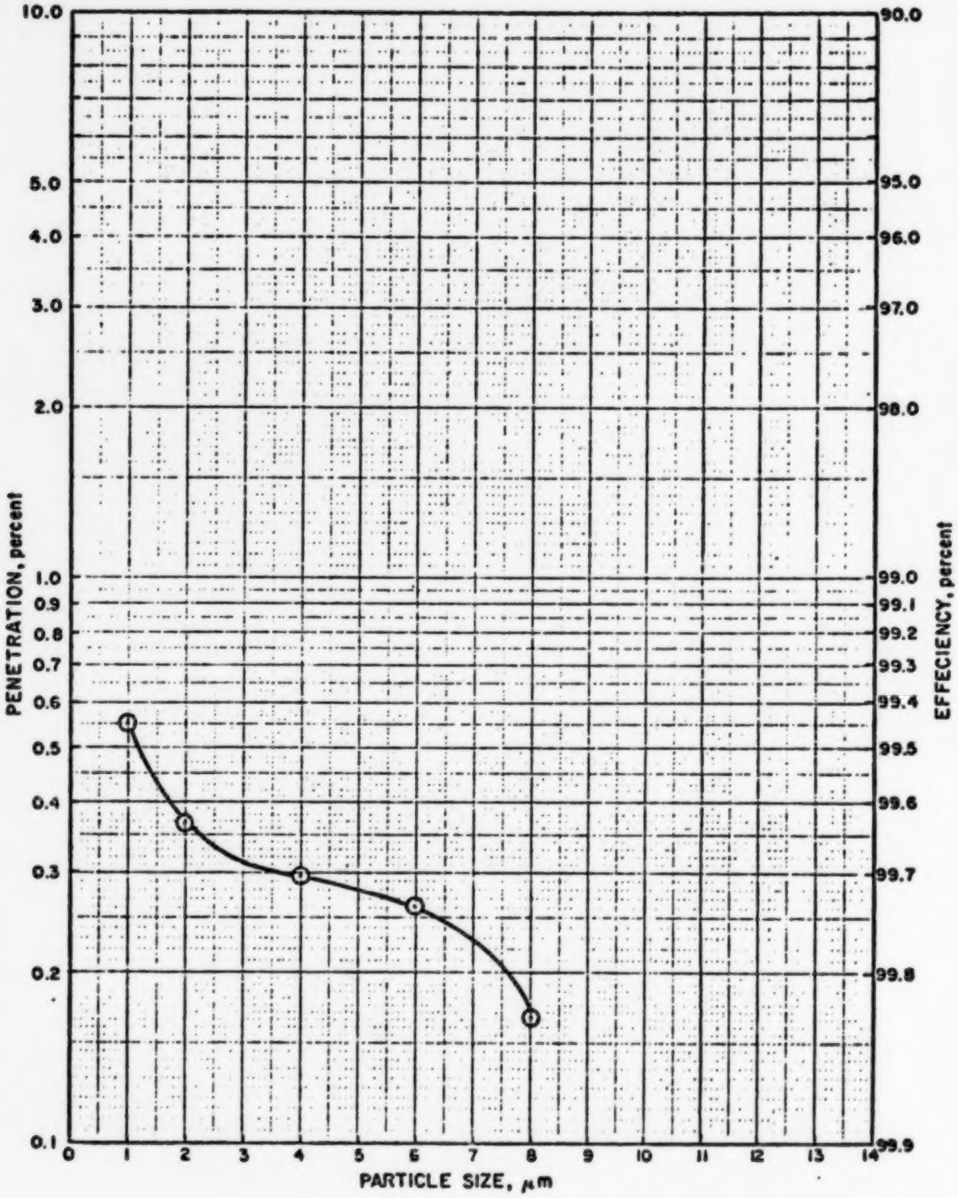

Figure 79. Penetration/efficiency as a function of size for Run 17

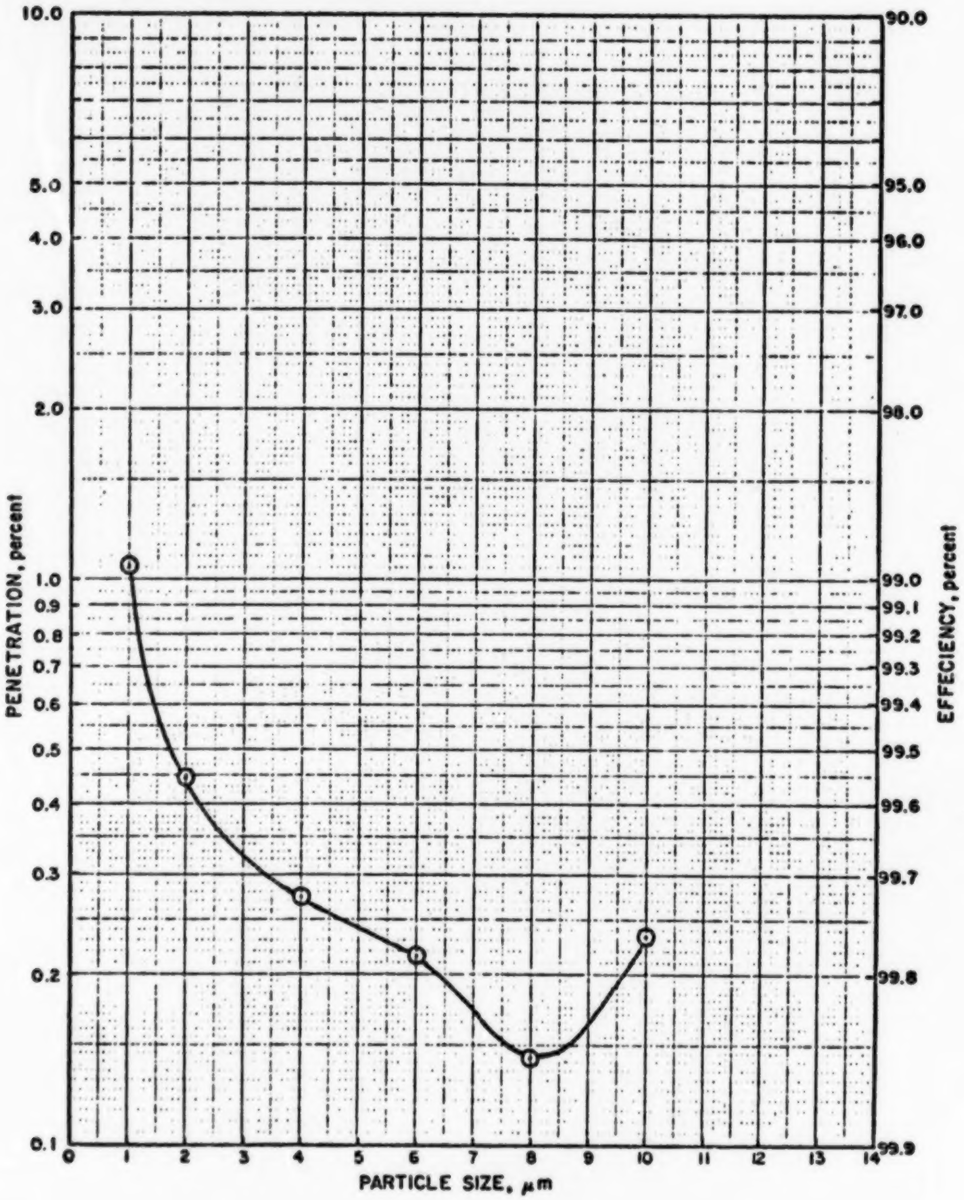

Figure 80. Penetration/efficiency as a function of size for Run 18

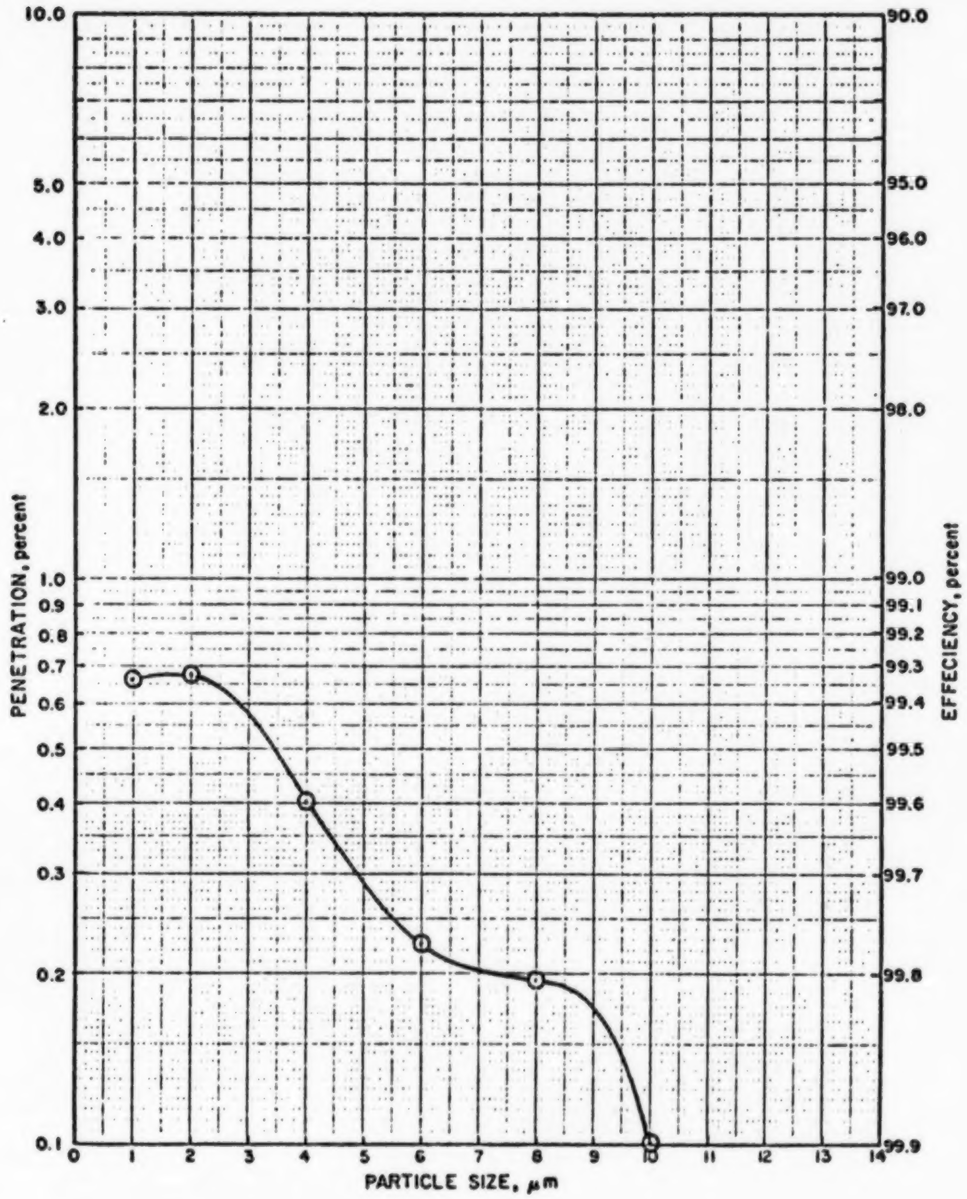

Figure 81. Penetration/efficiency as a function of size for Run 19

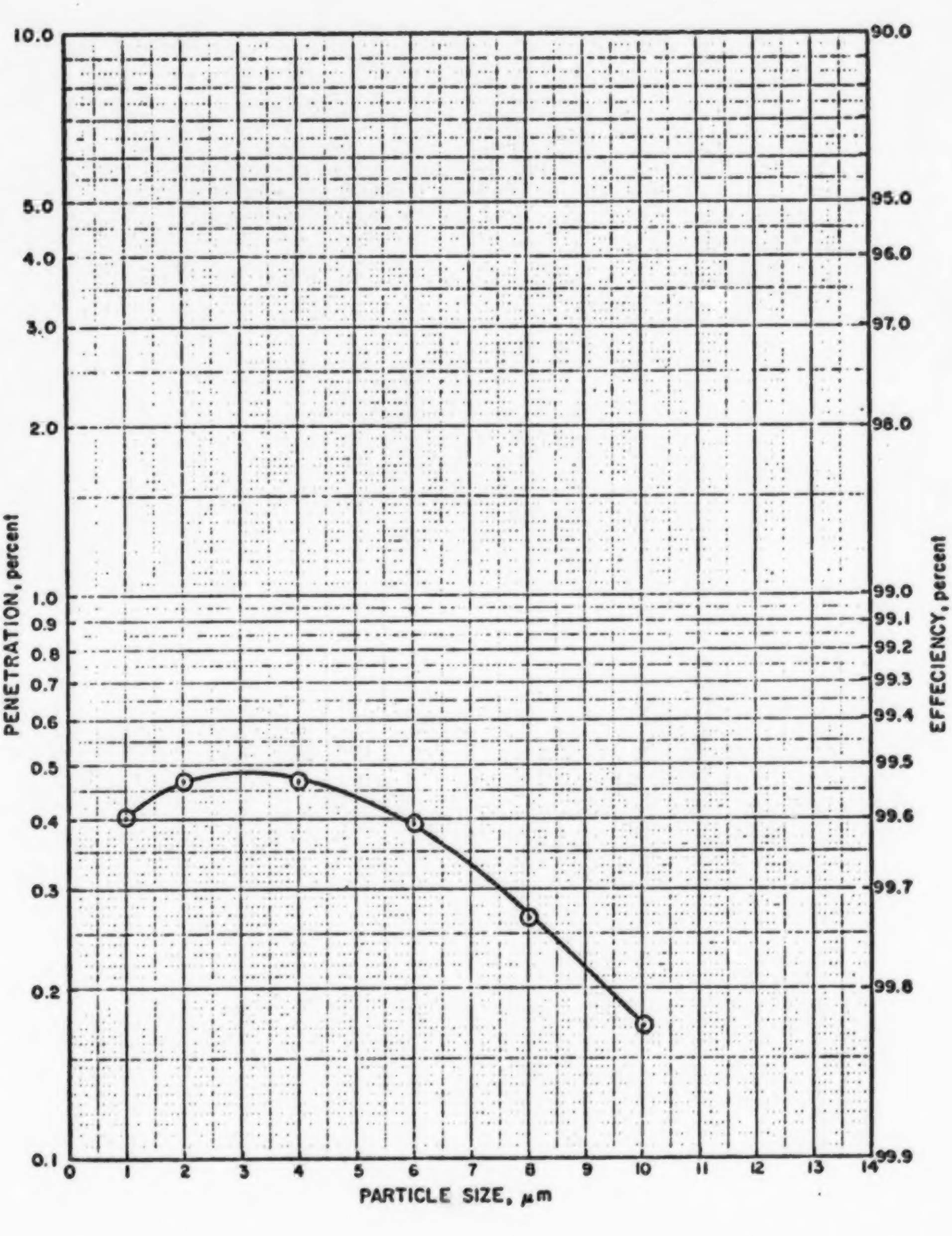

Figure 82. Penetration/efficiency as a function of size for Run 20

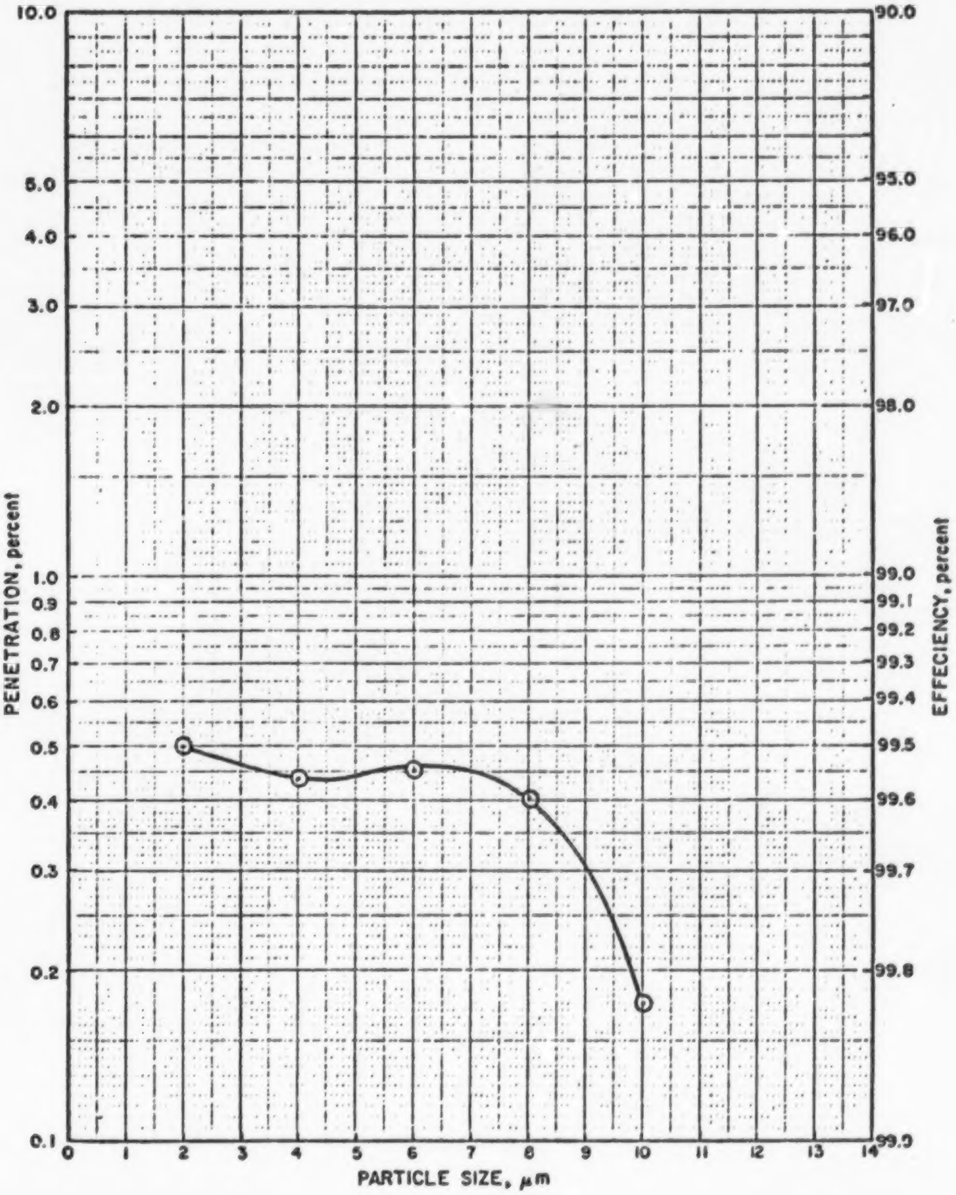

Figure 83. Penetration/efficiency as a function of size for Run 21

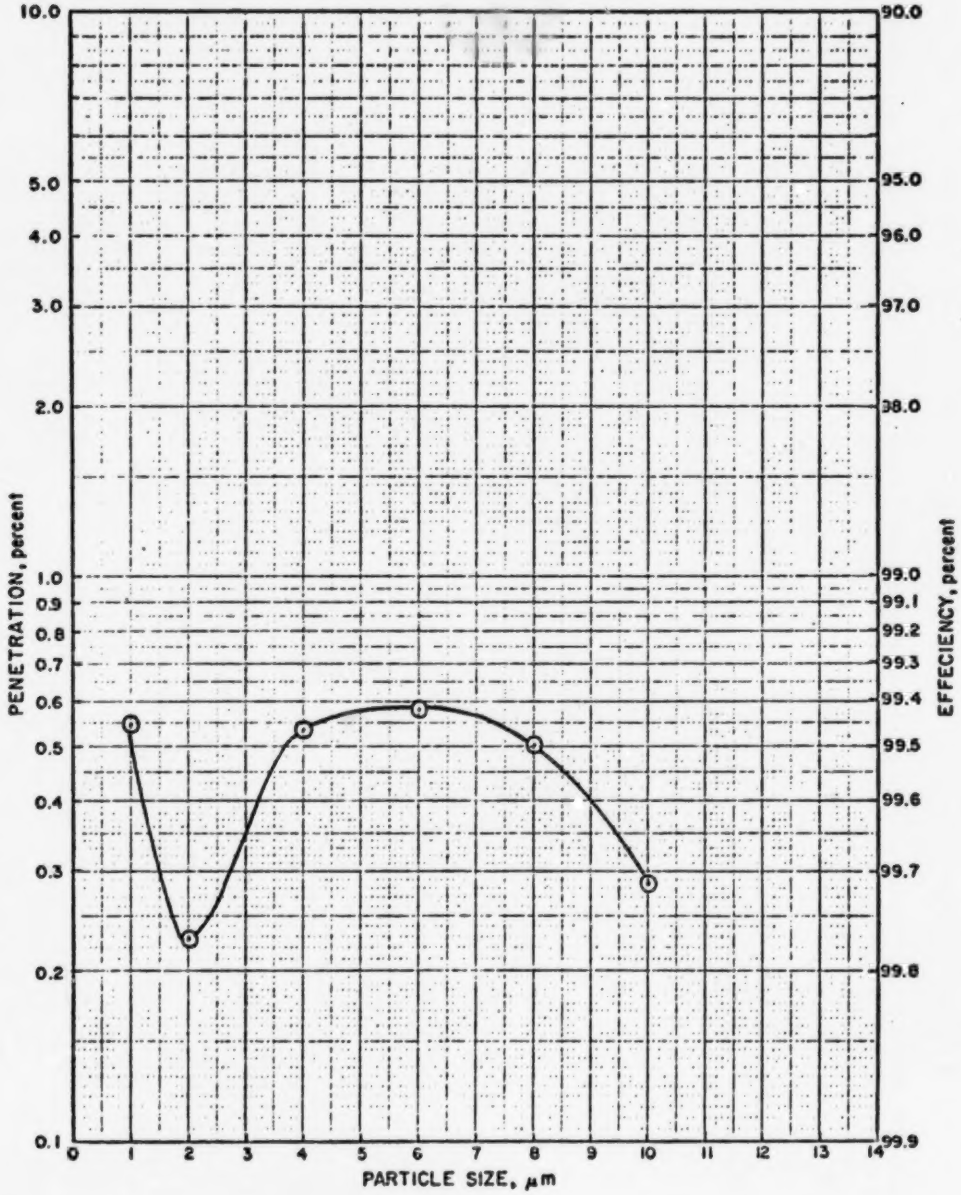

Figure 84. Penetration/efficiency as a function of size for Run 22

APPENDIX D

CNC READINGS

Table 14. CONDENSATION NUCLEI COUNTER SYSTEM DATA

Date	Time	Sample dilution system	Steady state conditions	DD flow (cc/sec)	Dilution ratio	Altitude corrected CNC readings (particles/cc)	Inlet concentration (particles/cc)	Outlet concentration (particles/cc)
9/26/74		D[a]	Yes	-	73	58,000		4,300,000
9/27/74		D	Yes	-	1.0	690		690
		D	Yes	66	1.0	340		340
		D	Yes	66	1.0	690		690
		D	Yes	-	1.0	660		660
		D	Yes	24	2.8	150		150
		D	Yes	66	1.0	690		690
		D	Yes	-	1.0	720		720
9/30/74		R[b] + AE[c] + D	Yes	-	220	27,000	6,100,000	
		R + AE + D	Yes	66	220	310	70,000	
		R + AE + D	Yes	66	220	600	130,000	
		R + AE + D	Yes	24	620	570	350,000	
		R + AE + D	Yes	66	220	390	86,000	
		R + AE + D	Yes	66	220	640	140,000	
		R + AE + D	Yes	-	220	31,000	7,000,000	
10/1/74	1100	D	Yes	-	3.6	700		2,500
	1125	D	Yes	66	3.4	680		2,300
	1140	D	Yes	-	3.4	690		2,300
	1210	D	Yes	66	3.4	690		2,300
		D	Yes	28	8.0	690		5,500
		R + AE + D	Yes	-	180	21,000	3,800,000	
		R + AE + D	Yes	66	180	540	97,000	
		R + AE + D	Yes	-	150	23,000	3,500,000	
10/1/74		R + AE + D	Yes	66	150	620	93,000	
		R + AE + D	Yes	28	350	570	200,000	
10/2/74	1030	D	No	-	1.0	730		730
	1055	C[c]	No	-	1.0	580		580
	1200	D + C	No	-	1.0	650		650
	1235	D + C	Yes	66	1.0	640		640
	1353	D + C	Yes	23	2.6	610		1,600

Table 14 (continued). CONDENSATION NUCLEI COUNTER SYSTEM DATA

Date	Time	Sample dilution system	Steady state conditions	DD flow (cc/sec)	Dilution ratio	Altitude corrected CNC readings (particles/cc)	Inlet concentration (particles/cc)	Outlet concentration (particles/cc)
	1400	D + C	Yes	3.7	16	610		10,000
	1525	R + AE + D	Yes	-	180	20,000	3,600,000	
	1540	R + AE + D	No	66	240	650	160,000	
	1605	R + AE + D	No	-	230	7,500	1,700,000	
	1627	R + AE + D	No	34	4.9	65	320	
	1637	R + AE + D	No	-	5.6	26	150	
	1645	R + AE	Yes	-	2.6	9,600,000	25,000,000	
	1655	R + AE	No	66	2.6	8,200,000	22,000,000	
	1715	R + AE	No	23	7.5	980	7,400	
	1720	R + AE	Yes	66	2.6	10,000,000	27,000,000	
	1723	R + AE	Yes	-	2.6	10,000,000	27,000,000	
10/3/74	1050	D	Yes	-	1.0	490		490
	1105	D + C	Yes	-	1.0	620		620
	1120	D + C	Yes	-	1.0	680		680
	1135	D + C	Yes	66	1.0	610		610
	1200	D + C	No	66	1.0	130		130
	1256	R + AE + C	Yes	-	2.2	11,000,000	24,000,000	
10/3/74	1323	R + AE + C	Yes	-	2.2	25,000	53,000	
	1332	R + AE + C	No	-	2.2	650	1,400	
	1340	R + AE + C	No	-	1.0	36,000	36,000	
	1425	C	No	-	1.0	26	26	
10/4/74	1025	P[e] + CT[f]	Yes	-	15	72		1,000
	1030	P + CT	Yes	-	1.3	78		98
	1035	P + CT	Yes	-	6.4	78		500
	1040	P + CT	No	-	1.6	72		120
	1055	P + CT	No	-	1.6	0		0
	1106	P	Yes	-	1.0	12,000,000		12,000,000
	1300	P + C	No	-	1.0	0 to 130,000		0 to 130,000
	1400	P + C	Yes	-	1.0	2,200,000		2,200,000[g]
	1430	P + C	Yes	-	1.0	13,000,000		13,000,000[h]
	1503	P + C	Yes	66	1.0	3,900		3,900

Table 14 (continued). CONDENSATION NUCLEI COUNTER SYSTEM DATA

Date	Time	Sample dilution system	Steady state conditions	DD flow (cc/sec)	Dilution ratio	Altitude corrected CNC readings (particles/cc)	Inlet concentration (particles/cc)	Outlet concentration (particles/cc)
	1550	P + C	No	24	2.6	420		1,100
	1610	P + C	Yes	-	1.0	320		320
10/5/74	1020	P + C	Yes	-	1.0	10,000,000		10,000,000
	1035	P + C	No	-	1.0	2,600,000 - 10,000,000		2,600,000 - 10,000,000
	1053	P + C	Yes	-	1.0	460		460
	1130	P + C	Yes	-	1.0	390		390
	1230	P + C	Yes	-	1.0	520		520
	1300	P + C	Yes	-	1.0	650		650
	1345	P + C	Yes	-	1.0	580		580
	1415	P + C	Yes	-	1.0	4,600,000		4,600,000
	1445	P + C	Yes	-	1.0	520		520
	1515	P + C	Yes	-	1.0	570		570
	1550	P + C	Yes	-	1.0	580		580
	1640	P + C	Yes	-	1.0	520		520
10/6/74	0912	P + C	No	-	1.0	4,200,000		4,200,000
	0930	P + C	Yes	-	1.0	12,000,000		12,000,000
	0953	P + C	Yes	-	1.0	12,000,000		12,000,000
	1020	P + C	Yes	-	1.0	12,000,000		12,000,000
	1110	P + C	Yes	-	1.0	12,000,000		12,000,000
	1135	P + C	Yes	-	1.0	11,000,000		11,000,000
	1206	P + C	Yes	-	1.0	11,000,000		11,000,000
	1220	P + C	Yes	-	1.0	12,000,000		12,000,000
	1255	P + C	Yes	60	1.0	12,000,000		12,000,000
	1320	P + C	No	60	1.0	0 to 260		0 to 260
	1345	P + C	No	60	1.0	0 to 200		0 to 200
	1500	P + C	Yes	-	1.0	12,000,000		12,000,000
	1559	P + C + CT	No	-	1.6	300		480
	1623	P + C	No	-	1.0	230		230
	1646	P + C	Yes	-	1.0	12,000,000		12,000,000
	1715	P + C	No	-	1.0	12,000,000		12,000,000

Table 14 (continued). CONDENSATION NUCLEI COUNTER SYSTEM DATA

Date	Time	Sample dilution system	Steady state conditions	DD flow (cc/sec)	Dilution ratio	Altitude corrected CNC readings (particles/cc)	Inlet concentration (particles/cc)	Outlet concentration (particles/cc)
10/7/74	0803	P + C	Yes	-	1.0	12,000,000		12,000,000
	0824	P + C	Yes	-	1.0	12,000,000		12,000,000
	0900	P + C	Yes	-	1.0	13,000,000		13,000,000
	0928	P + C + CT	No	-	12	50,000 - 200,000		590,000 - 2,400,000
	1030	P + C + CT	No	-	12	0 to 150,000		0 to 1,800,000
	1109	P + C + CT	No	-	12	50,000 - 200,000		590,000 - 2,400,000
	1115	P + C + CT	Yes	60	12	0		0
	1147	P + C + CT	Yes	60	12	0		0
	1335	R + AE	Yes	-	1.8	56,000	92,000	
	1400	R + AE	Yes	-	1.8	26,000	46,000	
	1434	R + AE	Yes	-	1.8	26,000	46,000	
10/22/74	1315	P + CT	No	-	4.6	70,000		320,000
	1330	P + CT	No	-	2.2	39,000		87,000
	1333	P + CT	No	-	2.0	26,000		52,000
	1403	P + CT	Yes	-	2.0	13,000		26,000
	1430	P + CT	Yes	-	2.0	13,000		26,000
	1630	P + CT	No	-	2.2	3,200		7,200
	1830	P + CT	No	-	1.5	10,000,000		15,000,000
10/23/74	0930	P + CT	No	-	3.0	9,000,000		27,000,000
	0945	P + CT	No	-	3.0	12,000,000		37,000,000
	1340	R + AE	Yes	-	1.9	140,000	270,000	
	1425	R + AE	Yes	-	2.1	140,000	300,000	
	1504	R + AE	Yes	66	2.1	130,000	270,000	
	1535	R + AE	Yes	33	2.1	120,000	240,000	
	1600	R + AE	Yes	3.7	35	5,100	180,000	
10/24/75	1040	R + AE	No	-	1.7	20,000	33,000	
	1125	R + AE	No	-	5.3	23,000	120,000	
	1140	R + AE	No	-	4.4	21,000	90,000	
	1200	R + AE	No	-	1.8	27,000	48,000	

Table 14 (continued). CONDENSATION NUCLEI COUNTER SYSTEM DATA

Date	Time	Sample dillution system	Steady state conditions	DD flow (cc/sec)	Dilution ratio	Altitude corrected CNC readings (particles/cc)	Inlet concentration (particles/cc)	Outlet concentration (particles/cc)
	1205	R + AE	No	55	1.8	18,000	32,000	
	1245	R + AE	No	55	1.6	16,000	24,000	
	1300	R + AE	No	6.8	16	0 to 1,600	0 to 25,000	
	1330	R + AE	No	6.8	16	0 to 1,300	0 to 20,000	
	1515	R + AE	No	-	1.4	0 to 1,300		0 to 1,800
	1520	R + AE	Yes	-	1.4	0		0
	1620	R + AE	Yes	-	1.4	0		0
	1630	R + AE	No	-	1.4	0		0
	1644	R + AE	No	-	1.0	10,000,000		10,000,000
10/25/74	1015	R + AE	Yes	-	1.6	6,000		9,500
	1020	R + AE	Yes	-	1.6	2,300		3,800
	1030	R + AE	Yes	-	1.6	3,600		5,700
	1040	R + AE	Yes	-	1.6	3,900		6,300
	1047	R + AE	No	-	1.7	5,800		9,600
	1055	R + AE	Yes	-	1.7	3,500		6,000
	1100	R + AE	Yes	-	1.7	4,400		7,500
	1130	R + AE	Yes	-	1.6	1,300		2,100
	1250	R + AE	No	-	2.6	7,400,000	19,000,000	
	1320	R + AE	No	-	2.0	260,000	520,000	
	1420	R + AE	No	-	2.1	6,500,000	12,000,000	
	1523	R + AE	No	-	3.1	320,000	10,000,000	
	1545	R + AE	No	-	2.7	220,000	590,000	
	1558	R + AE	No	-	2.6	91,000	240,000	
10/26/74	0920	R + AE	Yes	-	2.5	5,100,000	12,000,000	
	0940	R + AE	Yes	-	2.5	5,600,000	14,000,000	
	0956	R + AE	Yes	-	2.2	4,200,000	9,400,000	
	1027	R + AE	Yes	-	2.4	6,800,000	16,000,000	
	1045	R + AE	Yes	-	2.6	5,200,000	14,000,000	
	1102	R + AE	Yes	60	3.4	2,900,000	9,600,000	
	1135	R + AE	Yes	30	3.0	1,800,000	5,600,000	
	1142	R + AE	Yes	3.2	55	22,000	1,200,000	

Table 14 (continued). CONDENSATION NUCLEI COUNTER SYSTEM DATA

Date	Time	Sample dilution system	Steady state conditions	DD flow (cc/sec)	Dilution ratio	Altitude corrected CNC readings (particles/cc)	Inlet concentration (particles/cc)	Outlet concentration (particles/cc)
	1150	R + AE	Yes	3.2	55	13,000	710,000	
	1304	R + AE	No	-	1.7	22,000		38,000
	1320	R + AE	No	-	1.8	16,000		29,000
	1335	R + AE	Yes	-	1.8	6,100		11,000
	1405	R + AE	Yes	-	1.8	0		0
	1505	R + AE	Yes	-	1.8	3,000		6,400
	1541	R + AE	Yes	-	1.8	0		0
	1557	R + AE	Yes	-	1.8	0		0
10/27/74	0835	R + AE	Yes	-	1.6	0		0
	1013	R + AE	Yes	-	1.6	0		0
	1040	P + CT	No	-	1.7	0		0
	1112	P + CT	No	-	1.7	1,200		2,000
	1120	R + AE	No	-	1.7	0		0
	1137	R + AE	No	-	1.7	0		0
	1325	R + AE	Yes	-	5.5	5,700,000	31,000,000	
	1347	R + AE	Yes	-	6.1	5,700,000	35,000,000	
	1422	R + AE	Yes	-	7.6	6,500,000	50,000,000	
	1441	R + AE	Yes	60	7.1	4,400,000	32,000,000	
	1459	R + AE	Yes	30	6.9	2,500,000	17,000,000	
	1530	R + AE	Yes	3.1	170	26,000	4,400,000	
	1549	R + AE	Yes	3.1	170	26,000	4,500,000	
	1638	R + AE	No	-	4.0	2,300		9,400
	1701	R + AE	No	-	4.2	260		1,100
	1738	R + AE	Yes	-	4.2	12,000		49,000
	1800	R + AE	Yes	55	4.2	0		0

[a] Pump diluter.

[b] Large particle remover.

[c] Air ejector diluter.

[d] Condenser.

[e] Probe.

[f] Capillary tube diluter.

[g] Cleaning cycle minimum.

[h] Cleaning cycle minimum.

APPENDIX E

COAL ANALYSIS

Table 15. RESULTS OF COAL ANALYSIS FROM NUCLA BOILER NO. 2

Date and time	As received						Dry basis				
	Moisture (percent)	Volatiles (percent)	Fixed carbon (percent)	Ash (percent)	Btu per pound	Sulfur (percent)	Volatiles (percent)	Fixed carbon (percent)	Ash (percent)	Btu per pound	Sulfur (percent)
9/21/74											
0900	5.51	32.22	50.87	11.40	12,188	0.73	34.10	53.84	12.06	12,899	0.77
1400	8.99	30.31	47.93	12.77	11,145	0.61	33.30	52.67	14.03	12,246	0.67
1700	9.34	30.05	44.57	16.04	10,889	0.64	33.15	49.16	17.69	12,011	0.71
9/22/74											
0900	10.10	29.95	48.46	11.49	11,282	0.60	33.31	53.91	12.78	12,549	0.67
1330	7.34	31.46	48.56	12.64	11,359	0.71	33.95	52.41	13.64	12,257	0.77
1530	6.47	30.24	46.88	16.41	11,029	0.70	32.33	50.12	17.55	11,792	0.75
9/23/74											
0930	6.89	31.65	49.72	11.74	11,999	0.67	33.99	53.40	12.61	12,887	0.72
1420	5.09	31.73	49.52	13.66	11,847	0.86	33.43	52.18	14.39	12,482	0.91
9/24/74											
0850	4.41	32.79	50.40	12.40	12,159	0.64	34.30	52.73	12.97	12,720	0.67
1215	6.66	32.78	51.06	9.50	12,221	1,15	35.12	54.70	10.18	13,094	1.23
1700	5.64	33.45	50.53	10.38	12,379	1.36	35.45	53.55	11.00	13,119	1.44
9/25/74											
0915	7.05	33.24	50.28	9.43	12,305	0.97	35.76	54.10	10.14	13,238	1.04
1330	6.26	32.14	47.94	13.66	11,661	2.23	34.29	51.14	14.57	12,440	2.37
1550	6.11	32.74	47.47	13.68	11,744	1.63	34.87	50.56	14.57	12,509	1.74
9/26/74											
0850	4.58	33.27	50.83	11.32	12,354	1.08	34.87	53.27	11.86	12,947	1.13
1240	8.06	31.40	48.79	11.75	11,778	0.79	34.15	53.07	12.78	12,811	0.85
1525	6.86	31.49	48.59	13.06	11,760	0.67	33.81	52.17	14.02	12,626	0.72

Table 15. (continued). RESULTS OF COAL ANALYSIS FROM NUCLA BOILER NO. 2

	As received						Dry basis				
Date and time	Moisture (percent)	Volatiles (percent)	Fixed carbon (percent)	Ash (percent)	Btu per pound	Sulfur (percent)	Volatiles (percent)	Fixed carbon (percent)	Ash (percent)	Btu per pound	Sulfur (percent)
9/27/74											
0855	5.61	33.02	49.57	11.80	12,106	0.66	34.98	52.52	12.50	12,825	0.70
1245	5.67	31.06	48.86	14.41	11,725	0.60	32.93	51.79	15.28	12,430	0.63
9/28/74											
0355	5.25	32.06	50.50	12.19	12,072	0.66	33.84	53.29	12.87	12,741	0.70
1220	6.75	31.36	48.72	13.17	11,800	0.70	33.63	52.25	14.12	12,654	0.75
1530	7.02	30.77	47.71	14.50	11,455	0.65	33.09	51.32	15.59	12,320	0.70
9/30/74											
0910	4.48	32.66	51.27	11.59	12,238	0.66	34.19	53.68	12.13	12,812	0.69
1230	6.99	31.45	48.57	12.99	11,700	0.76	33.82	52.21	13.97	12,580	0.81
1525	6.31	31.34	46.44	15.91	11,234	0.71	33.45	49.57	16.98	11,990	0.76
10/1/74											
0900	5.01	32.05	47.19	15.75	11,486	0.55	33.74	49.68	16.58	12,091	0.58
1240	7.65	30.00	45.09	17.26	10,909	0.59	32.48	48.83	18.69	11,812	0.63
1520	6.96	30.01	45.60	17.43	10,985	0.56	32.25	49.02	18.73	11,807	0.60
10/2/74											
0900	8.15	29.92	45.37	16.56	10,990	0.64	32.57	49.40	18.03	11,965	0.69
1510	6.72	31.39	49.65	12.24	11,797	0.62	33.65	53.23	13.12	12,646	0.66
10/3/74											
1030	6.76	31.44	48.65	13.15	11,675	0.61	33.72	52.18	14.10	12,521	0.65
1315	7.63	31.15	48.47	12.75	11,650	0.70	33.72	52.48	13.80	12,612	0.65
1605	6.10	31.11	49.88	12.91	11,868	0.64	33.13	53.12	13.75	12,639	0.68

Table 15. (continued). RESULTS OF COAL ANALYSIS FROM NUCLA BOILER NO. 2

Date and time	As received						Dry basis				
	Moisture (percent)	Volatiles (percent)	Fixed carbon (percent)	Ash (percent)	Btu per pound	Sulfur (percent)	Volatiles (percent)	Fixed carbon (percent)	Ash (percent)	Btu per pound	Sulfur (percent)
10/4/74											
0850	6.20	31.77	48.95	13.08	11,830	0.63	33.87	52.19	13.94	12,612	0.67
1240	5.51	31.88	48.73	13.88	11,254	0.61	33.74	51.57	14.69	12,439	0.65
1450	5.60	30.81	50.32	13.27	11,889	0.58	32.64	53.30	14.06	12,594	0.61
10/5/74											
0905	5.55	31.77	50.85	11.83	12,145	0.59	33.64	53.83	12.53	12,859	0.62
1200	7.60	31.25	47.70	13.45	11,522	0.55	33.82	51.62	14.56	12,470	0.60
1505	5.68	32.19	49.14	12.99	11,905	0.63	34.13	52.10	13.77	12,622	0.67
10/6/74											
0905	2.79	32.79	52.86	11.56	12,556	0.56	33.73	54.38	11.89	12,916	0.58
1235	6.07	30.84	50.47	12.62	11,904	0.73	32.83	53.73	13.44	12,673	0.78
1500	6.01	31.22	48.22	14.55	11,663	0.68	33.21	51.31	15.48	12,408	0.72
10/7/74											
0745	7.36	29.62	47.37	15.65	11,284	0.96	31.97	51.14	16.89	12,180	1.04
1050	7.34	30.67	48.71	13.28	11,620	0.64	33.10	52.57	14.33	12,540	0.69
1325	6.06	31.36	48.96	13.62	11,785	0.76	33.38	52.12	14.50	12,545	0.81
10/22/74											
1120	7.68	31.03	47.27	14.02	11,149	0.77	33.61	51.20	15.19	12,077	0.83
1450	9.34	30.46	47.50	12.70	10,972	0.56	33.60	52.39	14.01	12,102	0.62
1745	8.25	29.06	46.86	15.83	10,581	0.55	31.67	51.08	17.25	11,532	0.60
10/23/74											
0330	7.40	30.38	48.51	13.71	11,177	0.70	32.81	52.38	14.81	12,070	0.76
1145	9.87	28.86	43.29	17.98	10,031	0.83	32.02	48.03	19.95	11,129	0.92
1550	9.77	29.74	47.02	13.47	11,004	0.64	32.96	52.11	14.93	12,196	0.71

Table 15. (continued). RESULTS OF COAL ANALYSIS FROM NUCLA BOILER NO. 2

Date and time	As received						Dry basis				
	Moisture (percent)	Volatiles (percent)	Fixed carbon (percent)	Ash (percent)	Btu per pound	Sulfur (percent)	Volatiles (percent)	Fixed carbon (percent)	Ash (percent)	Btu per pound	Sulfur (percent)
10/24/74											
0855	7.33	31.16	50.16	11.35	11,451	0.54	33.62	54.13	12.25	12,357	0.58
1155	9.63	30.21	46.95	13.21	10,854	0.62	33.43	51.95	14.62	12,011	0.68
1715	9.18	31.46	47.61	11.75	11,270	0.70	34.64	52.42	12.94	12,409	0.77
10/25/74											
0905	7.19	31.53	48.76	12.52	11,434	0.61	33.97	52.54	13.49	12,320	0.65
1155	7.51	29.44	47.33	15.72	11,101	0.56	31.83	51.17	17.00	12,002	0.60
1445	6.85	30.44	49.19	13.52	11,545	0.67	32.68	52.81	14.51	12,394	0.71
10/26/74											
0815	7.26	31.32	49.53	11.89	11,690	0.59	33.77	53.41	12.82	12,605	0.63
1115	9.06	30.19	46.91	13.84	11,034	0.78	33.20	51.58	15.22	12,133	0.86
1520	7.92	30.44	48.48	13.16	11,217	0.70	33.06	52.65	14.29	12,182	0.76
10/27/74											
0845	6.60	31.52	49.37	12.51	11,672	0.66	33.75	52.86	13.39	12,497	0.71
1105	9.55	29.71	47.42	13.32	10,863	0.71	32.85	52.42	14.73	12,010	0.78
1515	8.97	29.49	48.44	13.10	11,202	0.69	32.39	53.22	14.39	12,305	0.76